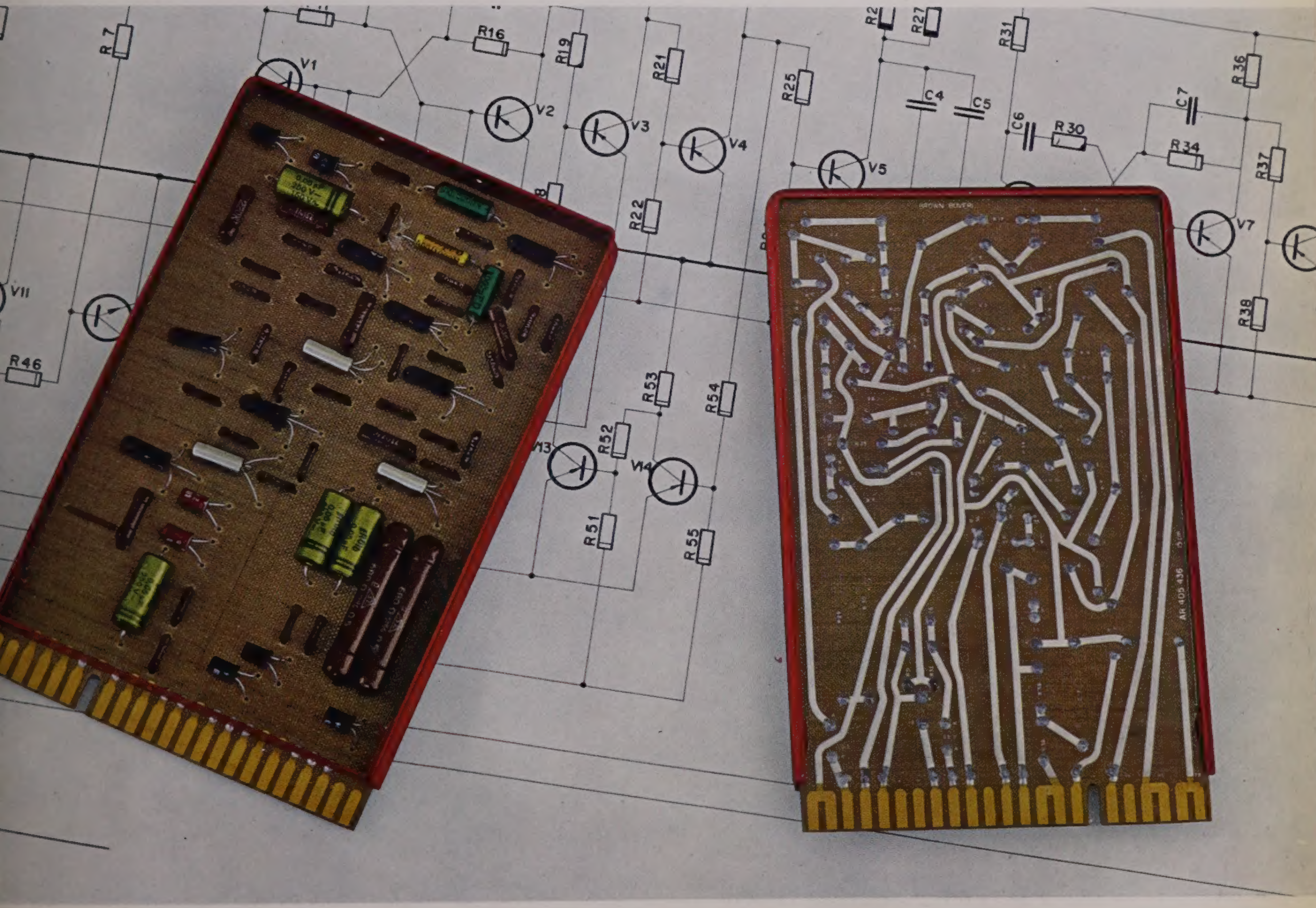
BROWN BOVERI REVIEW

Electronics in Industry and Power Systems



These printed circuits are typical elements from the extensive Brown Boveri electronic system, a unit construction system for electronic control and tele-operation tasks

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Control desk of a digital system controller used for controlling the exchange of power between Switzerland and the neighbouring countries

On the left-hand side are the indicating and operating elements for one system controller. The upper part of the desk contains six correction outputs for dosage of the correction and its communication to the controlling generating stations

THE BROWN BOVERI REVIEW

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Introduction

ON THE occasion of the first International Congress and Exhibition for Instrumentation and Automation (Interkama) in 1957 a special issue of this journal was published, headed "Automatic Control Systems and their Elements". From this review it was apparent that the Company have at their disposal a large number of electro-mechanical, hydraulic, pneumatic, magnetic and electronic elements, which may be utilized in solving a particular problem, depending on the conditions encountered.

Once again Interkama, as an international event, offers an opportunity to publish a number of articles describing the present position in the fields of control engineering and measuring techniques. In view of the vigorous development at the present time, such progress reports are to be welcomed. They not only indicate the standard attained, but also give an idea of the direction which developments are likely to take and thus give an insight into the future, which is most desirable for planning investment.

The present issue, published specially for the Interkama 1960, concentrates on the design principles and possible applications of electronics in industry and power systems. This is solely because electronic solutions have tended to shift into the focus of interest, due to the introduction of semiconductors, and permit the organization of a standardized system. Electronics, in its widest sense, is a sphere of activity which has been intensively exploited by the Company for the last 25 years, primarily in the field of high-frequency engineering. In this sphere, as well as in the field of information handling, a position has been reached at which, due to the vigorous efforts to develop techniques of their

own, the most modern requirements can be fulfilled, as described in a special issue of the Brown Boveri Review (No. 11/12, 1959) devoted to Information Handling Techniques.

Experience gained so far, together with the possibilities afforded by the new components, induced Brown Boveri to create a series of standard circuit elements suitable for use in the widespread field of automatic control, for many of the associated problems of measurement, and at the same time for tele-operation and for problems of information processing in the wider sense.

This system is based on a methodical analysis of the tasks which have to be performed and the means of carrying them out. In order to meet the widely different requirements, e.g. as regards the power level and working speed, a number of distinct ranges were created, incorporating both analogue and digital units, employing standardized signals, and with matched input and output impedances.

By combining such elements it is possible to create both simple and extremely complex circuit arrangements complying with the requirements of many different spheres of application. It also becomes possible to reduce the amount of engineering work and simplify manufacture.

The description of the characteristic features of this new system, introduced under the name of the Brown Boveri Electronic System, occupies the greater part of the present issue. With the elements and units of this system which are all based on a "building block" principle, together with equipment used formerly, it will be possible to put forward the most expedient solution to any problem in the spheres of automatic, open or closed-loop control, tele-operation, and so on.

(KME)

A. DE QUERVAIN
E. H. LUDWIG

FUNDAMENTAL ASPECTS OF THE BROWN BOVERI ELECTRONIC SYSTEM

621.38

The present article explains why different elements are required for various control processes in engineering and demonstrates that, due to their inherent similarity, these elements can be designed on a "building block" principle. Brown Boveri have developed a system of this kind, with four distinct ranges for different fields of application. The question of the choice of the most suitable standard signal, also the problem of power level, is dealt with in detail. In conclusion, some of the main technical features are discussed.

IT IS inherent in the nature of automation for man to be relieved of a great many repetitive mental tasks, such as controlling, measuring, memorizing, calculating, taking logical decisions, in fact information handling in its most general forms. The variety of the tasks thereby posed is extremely large, and continues to increase, in the same way as the degree of interrelation between the individual stages of an industrial manufacturing process. Hence it is becoming increasingly difficult in a particular case, for example a new automation project, to arrive at an economical solution which is technically an optimum at the same time, and involves only a reasonable amount of engineering work. Taken all round, every practical task is quite different from the next, and yet there is a certain amount of similarity between some aspects which are continually repeated, and for which the same solution can be adopted.

Therefore an effort must be made to resolve all problems into a series of separate tasks and to find solutions to these by adopting a unit construction system. Then only the variety and nature of the combinations of individual solutions differ from one application to another. A system of this kind will effect savings in all stages of a manufacturing process, e.g. in the planning stage, design and manufacture, as well as during erection and commissioning, and as regards maintenance and the storage of spare parts. In developing such a system the aims should be as follows:

The system should permit clear and flexible planning in order to reduce the amount of work involved when projecting installations.

The principles and solutions adopted should be as nearly uniform as possible, both from the constructional and electrical aspects, in order that maximum combination may be possible.

The constructional elements should be optimalized with regard to type and size, so that their manufacture, testing and application can be economical over as wide a range as possible. Above all, in this range, under normal circumstances, there should be no need for any special supplementary developments.

Individual components must fulfil the severest requirements with regard to reliability, in order to reduce the risk of failure, even in large installations.

Maintenance should be reduced to a minimum, and it should be possible for relatively unskilled personnel to carry it out.

Brown Boveri solved these problems with a system of "building blocks". The basic units, which will be referred to later, are constructional entities, designed as self-contained circuits capable of performing one or more specific functional tasks. Each unit is denoted by its own characteristic number as part of a system.

Organization of the Unit System

Aspects of Definition of the Individual Elements

The organization of the entire range of units should be such that a minimum of special tasks have to be performed in the solution of any practical problem. This is most difficult to avoid during the planning stage, where the most favourable solution has to be found with the means provided by the available units of the system. However, the more design work can be reduced, the more easily the designer is able to derive the design from the results of planning. This gives rise to the requirement that planning and design must work with analogous building blocks. Let us briefly examine what is meant by this.

The planning of an installation is based on the functional requirements for the various factors involved in the process and as laid down in the specification. In order to master the complex interconnections which may exist between these factors, they must be resolved into a network of subsidiary links of the simplest possible nature, each of which only represents one relatively simple functional relationship between a few factors. These may be referred to as basic functions. For a unit construction system a properly graduated selection of building blocks must be available, to enable all functional requirements to be fulfilled. To give a clear idea of what is intended, planning must at least produce a functional circuit diagram (block diagram) in which the normalized basic functions are denoted by appropriate symbols. Complete functional groups, that is to say, frequently recurring combinations of several basic functions forming complicated relations, may also be denoted by combined symbols in certain cases. Lines linking the symbols indicate the signal flow. Thus we have a form of unit system in which functional elements are the units.

The block diagram must be realizable in the electrical design by corresponding circuits. For each normalized basic function or group of functions, therefore, corresponding normalized basic circuits or groups of circuits must be available, if special development work is to be avoided in the preparation of a single installation. In practice it must be as easy to combine these circuits as visualized in the function diagram. This in turn imposes conditions regarding the nature of the signals between the various circuits, which will be dealt with later. If the analogy basic function—basic circuit, and combination of functions—combination of circuits, is carried out consistently, it is quite a simple matter to derive the overall electrical circuit diagram from the functional block diagram. This circuit diagram will also be very similar in structure to the block diagram.

Analogously, constructional units must also be available for the mechanical design, which correspond as nearly as possible to the circuit and functional elements.

The advantages of the procedure described are obvious: Planning is greatly simplified, while the work involved in drawing up the circuitry and overall design is considerably reduced. Provided standardization is not taken too far, the attainable savings in this case appreciably outweigh the possibilities which are not utilized with the units in a particular system. Therefore, as will be explained later, the Brown Boveri electronic system comprises a number of different ranges for different applications.

The principles outlined above were adopted for all the ranges. In the process the uniform use of transistors and diodes actually permitted the evolution of a "building block" principle of construction, which is equally applicable to the elements of all ranges [1].

Organization in Unit Groups

The electronic system has to be capable of performing such duties as open-loop, closed-loop and automatic control as are experienced in electronic computers or data processing. Input data are processed to yield new output data. In line with the nomenclature which has become accepted in this field, it is possible to distinguish between the following groups of units:

(a) *Input units*

They undertake the conversion of the actual values of the process (states to be monitored, measured values) and the desired values (commands or reference values set by hand or imparted by stores for the process variables) into a form suitable for further processing.

(b) *Control units*

Their task is to correlate the input data in a predetermined manner. As a result they give new commands, or produce new reference values necessary for the process to follow the desired course at any moment.

(c) *Output units*

They amplify and, perhaps, convert the imparted commands into a form in which they can influence the course of the process via *correcting* elements. They also give signals of a purely informatory nature, which have no effect on the process whatsoever.

(d) *Auxiliary units*

They perform auxiliary operations which are indirectly required to enable the first three to perform their own functions (e.g. power supply).

The tasks which the input and output units have to perform are extremely widespread. For conversion of the process variables sensors are required, for almost all physically measurable quantities, with different measuring ranges and for different requirements as regards accuracy and price. Even the simple task of setting a desired value necessitates a whole series of different units, depending on whether the value has to be set frequently or not, on the precision with which it should be received, and whether the setting must be carried out from one or more places. The final control units differ, not only with respect to the physical quantities they can influence, but also according to their power and control range.

The tasks of the control units, in contrast, involve only a small number of basic operations which are continually being repeated.

In order to cover the entire field of closed-loop, open-loop and automatic control with as few different elements as possible, it is obviously advisable to follow these lines:

Input units are so designed that they transfer their result to the control units in a well defined manner, namely as a standardized signal.

The control units are designed to perform the basic operation with standardized signals.

The output units are designed to be controlled and actuated by standardized signals received at their inputs.

Organization According to Field of Application

The requirements stipulated regarding the units from the practical side, particularly as regards the speed, power level, complexity of organization, robustness both from the electrical and mechanical point of view, in some cases differ appreciably according to the application. The same applies to the ambient conditions under which they have to operate. It is of course quite out of the question for a particular functional task to be performed economically with the same combination of units in every case, in view of the many different applications which are possible. To meet all requirements a solution of this kind would have to possess numerous properties which, while making it more expensive, could never be utilized simultaneously.

Considering the wealth of possible applications, it can fortunately be established that there are some very large fields of application in which the same combination of requirements is continually being encountered. It is thus possible to choose the optimum combination of units for such fields, i.e. they can be "tailor-made". The result is a number of different ranges of units.

Among the fields of application control engineering occupies the leading position. Its main stress is on analogue methods, i.e. the employment of continuously changing signals. A later article

discusses this subject. No less important, though, is control, with its wide variety of applications, beginning with simple forms of follow-up control and extending right up to extremely complex and rapid digital circuits, such as are required for performing digital calculating operations, as discussed in subsequent articles in this issue. In practice, control engineering usually involves a close mesh of relations. Thus, with analogue control methods for instance, it is not always possible to dispense with purely switching operations, either on the input side or, more especially, on the side of the output units. When the Brown Boveri electronic system was being designed, special attention was devoted to this point. A uniform technique was devised which bridges the apparent gap between analogue and digital techniques. The individual ranges therefore contain analogue and digital units on principle, although of course the one is liable to be preponderant in a particular range.

When dividing up the ranges another important point had to be taken into consideration, namely the actual distance between individual parts of an installation. If this is small, a wider choice of communication links is available for the exchange of information between individual points, without this involving undue outlay. The information can be exchanged along parallel lines. Since every item of information is characterized by its own communication route, coding is practically unnecessary. For the majority of practical requirements two ranges are sufficient, these are:

(a) *Range 1 (Power engineering applications)*

This range contains units for open-loop control, analogue closed-loop control and automatic control in industry. The main requirements are concentrated on high mechanical strength and insensitivity to external electrical disturbances. The power involved is relatively high, the working speed low. The control units have only to perform fairly simple operations with comparatively low accuracy, and make quite simple logical decisions.

(b) *Range 2 (Counting applications)*

These units are intended for rapid controls, for the digital and automatic control of machine movements. Compared with the requirements which have to be fulfilled by range 1, the conditions regarding robustness are somewhat reduced. The power level is much lower but the working speed is very much higher. The main task of the control units is to count and evaluate periodical phenomena.

Units of ranges 1 and 2 can be employed without modification to solve certain tasks imposed by the protection of power systems. This is particularly true of complicated protective duties, in which calculating operations have to be performed. On the other hand, the price position on the transistor market does not offer any immediate prospects of a rapid development towards simple contactless protective devices.

A further additional range has been created for those cases in which the individual parts of an installation are so widely separated that the exchange of information between the various places can only take place over a single communication link at a time. This is:

(c) *Range 3 (Tele-operation)*

These units are used to reliably transmit a large number of control commands of all kinds, position indication signals and measurands, using only one conductor. As regards robustness, power level and operating speed they roughly correspond to the units in range 2.

The main task of the control units is coding and decoding commands and incoming information, testing for undisturbed transmission, and the introduction of a time graduation for signals which may possibly be received simultaneously.

The last range, which is designed for extremely high counting rates, is:

(d) *Range 4 (Computer applications)*

The units of this range are designed to solve those tasks in which complicated, logical decisions have to be made at very great speed, and arithmetical operations performed with great accuracy. Typical applications are digital control systems permitting deviations from the desired value of less than 0·01%, and arrangements enabling the optimum performance to be obtained with a particular process. The power level corresponds approximately to that

of range 2, the robustness is slightly reduced but the operating speed is a whole order of magnitude higher.

Factors Governing the Choice of Standardized Signals

Despite the graduation of the different ranges, an essential stipulation is that the units from the ranges should be interchangeable with their counterparts, if necessary. This is most likely to occur with the units of ranges 1 and 2. As an example we may take a machine tool, the working sequence of which is rendered largely automatic by means of a punched-tape control system. On account of the speed required, the majority of the tasks which have to be performed can only be fulfilled with units of range 2. Among these are, for instance, measurement of positional coordinates by digital methods, or the evaluation of commands and reference values stored on the tape. A not inconsiderable part of the tasks clearly belong in the realm of power engineering and are accordingly fulfilled by units of range 1. These include, for example, the control of drive elements for the feed. The stipulation of easy combination is evident in this example, most of all in the control units, where signals from or for the drive equipment and measuring system have to be correlated logically or functionally. For this to be made feasible in a simple manner it was necessary to ensure that the standardized signals of the various ranges are practically identical, or very easy to convert from the one form to the other. This automatically makes the control units of one range combinable with the input and output units of the other.

The choice of the standardized signals is most important for the design of the system as such. At the present state of engineering there is no doubt at all that electrical quantities are most suitable for processing the signals in the control units. However, the question which is not so clearly decided is whether the standardized signal should be a voltage or a current. For the widespread systems used for telemetering, and for the measurand converter based on the principle of automatic torque compensation, a current has become the accepted standard signal. For systems covering less space, especially where the measurand already exists in electrical form or can be converted into an electrical quantity without the assistance of moving mechanical parts, a voltage is probably more suitable as standard signal. Above all, this has the advantage of being suitable for distribution to various receivers at the same potential by simple means. The magnitude of this voltage is governed primarily by the elements employed in the control units. The frequency and phase angle of an alternating voltage can also be used as carriers of information, but are only likely to be considered in exceptional cases, e.g. for transmission over very long distances, or for storage on magnetic tape. From the above considerations voltages were finally chosen as the standard signals.

Now the question arises regarding the number of standard signals which are needed, or convenient. In this case it is best to consider the input and output values which have to be processed.

Let us first consider the desired and momentary values of process quantities, which are subject to continuous or discontinuous change and which do not have to be processed with unduly great accuracy (order of magnitude of 0·1%). The Brown Boveri electronic system uses a d.c. voltage for such signals, the magnitude of which is proportional to the particular quantity which has to be transmitted, and whose maximum value corresponds to the maximum possible value which the quantity can reach in the system. With physical quantities which can occur in two directions, for instance speed or acceleration, the direction can be indicated by the sign of the signal. Since an analogy exists between this signal and the measured value, or the correcting condition, and since further processing of this signal, especially integration and differentiation, is performed by circuits providing an analogy to the corresponding mathematical operation, this signal is referred to as the "analogue" or A signal. To define the limit between it and the C signal described later, it is pointed out that an analogue signal does not always have to vary continuously. It is quite possible, for example, for a desired value to vary abruptly. The units used for processing an analogue signal are referred to as analogue units.

Apart from the variable quantities, it is also necessary to analyse states, or to receive and pass on commands which can only possess two distinct forms, and can thus be expressed by a simple "Yes/No" decision. For instance, a particular state is either attained or not attained, a command has been given or not given, an output unit has or has not to operate. Simple examples of input units of this kind are the push-button and limit switches on a machine, while typical output units are magnetic couplings and indicator lamps. For those cases where more than two definite states are visualized, e.g. a motor with follow-up control, which is either stopped, or runs forwards or in reverse, the command can be a combination of several yes/no decisions; for the above motor these may, for example, be one for forwards and one for reverse. It is convenient also to use a voltage for the signal for such yes-no decisions, and it may be permitted to vary in a predetermined range, both for yes and no, without affecting the result. The two variable zones are separated from one another by a sufficiently large "forbidden" zone which has to be crossed at not less than a certain minimum speed when changing from state to state. By defining these zones it is possible to receive an accurate result with units of only a relatively low accuracy. Thus, for example, the stipulation that the output resistance of a unit must be small compared with the input resistance of the unit connected to it, which is essential for analogue elements in view of the accuracy required, does not have to be fulfilled by units which only have to take yes-no decisions. A signal whose information content is restricted to only two definite states can be considered as the simplest form of code (subsequently referred to as C signal). Units which handle C signals may be regarded as digital units.

Code signals are most important when the magnitude of a quantity has to be analysed with an accuracy which is beyond the capabilities of analogue units. Suppose, for instance, a position has to be determined to within 0·01 mm in a total distance of 10 m, this represents a relative accuracy of 10^{-6}. This is well outside the scope of analogue units. It is solved by expressing the measured quantity as a multiple of a basic unit. The control units then only operate with this number. For example, a coordinate of 9753·10 mm is represented by the number 975310 when the basic unit is 0·01 mm. The signal expressing this number must be of such a form that the control units can process it faultlessly if the accuracy of the final place is to be retained. From the foregoing reasons only the C signal can be considered in such cases. Conforming to the numerous places and values which these digits may have, in a single number, the signal representing every single number must consist of a combination of so many individual C signals that each value in the row of numbers can be allotted a different combination from every other (coding). If, for instance, we denote the "yes" decision in the usual manner by the code 1, and "no" by 0, the number 14, using the excess-3 code as in the units of range 2, can be represented by the code 01000111, a digital signal. Units handling these signals are known as digital units. The change from the analogue measured quantity to the digital representation, and vice versa, necessitates analogue-to-digital and digital-to-analogue converters.

The individual digital or C signal always has a definite value, either 1 or 0. If its value is known at a given moment, new information is not received until it changes to the other value. Thus, in principle, no information is lost if the control units only analyse this part and store the state attained in the meantime. This procedure can, for instance with fast control units, even lead to a cheaper solution. A signal which only describes the boundary transfer from 0 to 1 and vice versa, is obtained by differentiation of the C signal with respect to time. It consists of brief voltage pulses, the polarity of which alternates according to the nature of the transfer. It is referred to as the differential (derative or D) signal and is largely employed in the units of ranges 2 to 4.

In addition to providing facilities for combination between different ranges, it is important to ensure

that analogue and digital control units of the same range work together easily in an installation. This imposes additional conditions regarding the choice of the signals, special reference to which is made in the articles on pages 676 and 682. Above all, it is necessary for the converters mentioned above to provide the transition between the analogue and digital units.

Important Technical Features

Control Units

The question as to what are the most suitable elements for the construction of the control units is fairly easily answered at the present state of engineering progress. For the execution of most of the operations involved an amplifying action is necessary. Until a few years ago only transductors and electron tubes were available for this task. In the meantime cold-cathode tubes and semiconductor elements (transistors and diodes) have joined them as components.

Unfortunately, on account of its heated cathode, the life of the electron tube is limited. The working speed of transductors is limited, primarily by the supply frequency, and—at least at 50 c/s—is no longer adequate in many cases.

For the special task of storing digital signals, good results have been obtained with circuits employing small ring cores having a rectangular hysteresis loop. These are capable of storing information even after the supply voltage has failed and they do not occupy much space. In such cases, though, ring cores have no amplifying action and must be fed by electron tubes or transistors.

The cold-cathode tube has a discontinuous action and can therefore only be used for digital operations. Disturbing factors in practice are often the high working voltage, the loss of controllability of an ignited tube, and the effect of ageing.

Only semiconductors, i. e. transistors and diodes, provide components exhibiting none of the listed disadvantages. They are very small and ideal for use with printed circuits. They are insensitive to shock and have an almost unlimited life. When they are used, the number of spare parts which have to be stocked can be reduced to a minimum. With the small units it is even possible to take advantage of the facility for moulding the unit completely in synthetic resin, or to coat a complete circuit with a protective material, since the likelihood of a unit failing is so slight that it is worth taking the risk of having to replace the whole unit (Fig. 1). The effect which the dependency of certain characteristic values of transistors on temperature has on the function of the circuit no longer presents any difficulties. By suitably dimensioning the circuit and, if necessary, using silicon transistors, it can be kept within the admissible limits.

For these reasons transistors and diodes are used almost exclusively in the control units. Cold-cathode tubes and ring cores are only employed in very rare cases, for which their special properties can be utilized with advantage.

Load Capacity of Individual Units

As already stated, the output signal of a unit can be applied to the inputs of several subsequent units by branching. Such branches already exist in quite simple control systems and are frequently encountered in control engineering. The number of units which may be connected depends on the load capacity of the individual units. For universal applicability it would be ideal for this capacity to be as large as possible. But, on the other hand, the load capacity of a unit also governs its price, and it would be uneconomical to make the capacity so large that it could not be fully utilized in the majority of cases.

The aspects that decide which is the most favourable compromise in this case vary with the application. Thus the load capacity is different from one range to the next. Nevertheless there is an important difference between range 1 and the others. On account of the wideness of the field of applications and the stipulated facilities for combination, provision had to be made in range 1 for a sufficiently flexible applicability. The additional cost was low

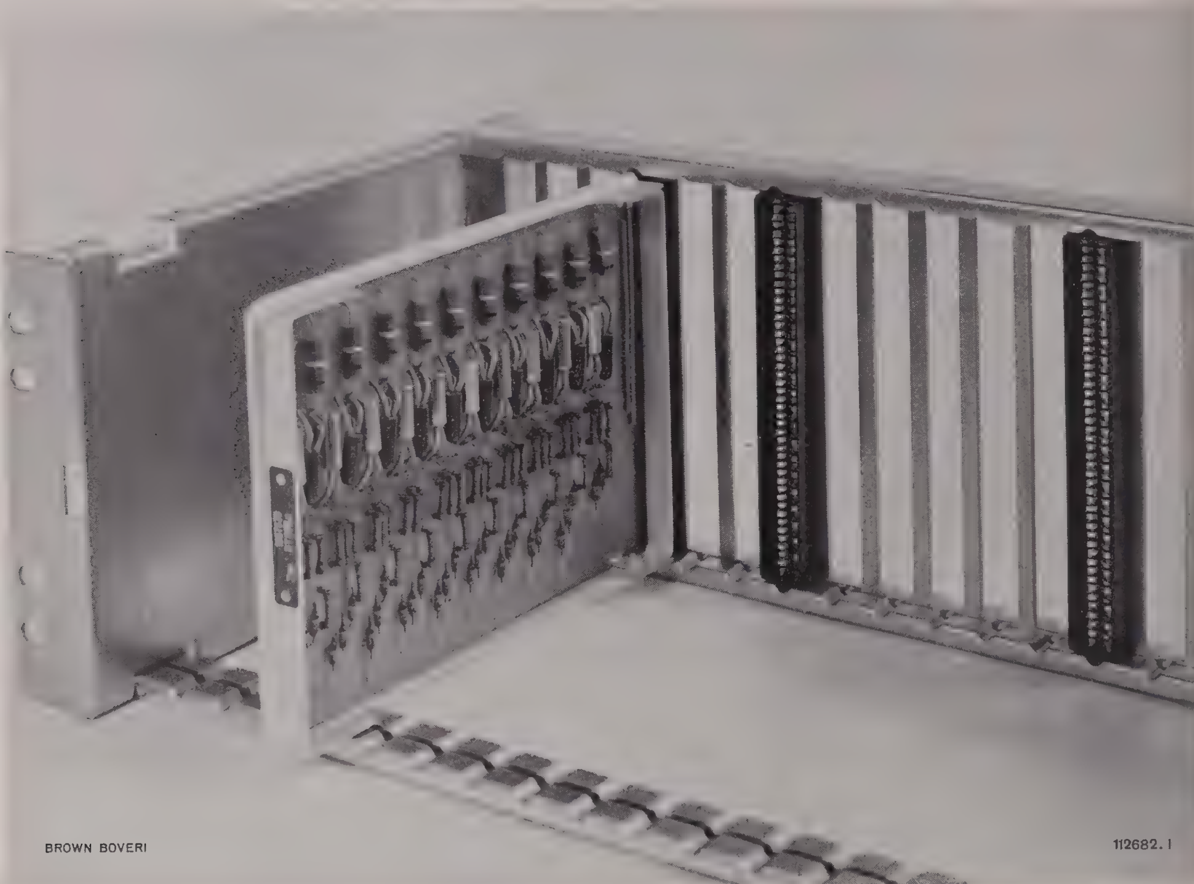

Fig. 1. – Plug-in printed circuit complete with guide rail and contact system

because the necessary low-frequency transistors are nowadays available at reasonable prices. With the other ranges the flexibility is far more limited by the practical and economical requirements. But even here precise load tables greatly simplify the task of planning.

Power Level in the Control Units

Closely related to the question of load capacity is the question of the power level in the individual units. In order to render the units insensitive to capacitive and inductive disturbances, the power should be as high as possible. The output units would also be cheaper if the power level in the computer was not unduly low. On the other hand, fixing too high a power level makes the power supply more expensive and to radiate this power a complex circuit must possibly be made still more complicated than the size of the elements really necessitates. But since the question of reliability takes priority over the question of power supply, the decision must be made for reliability, i.e. freedom from disturbance, by having a sufficiently high power. But in doing so, adequate overload protection must be afforded for the transistors. Only in this way is it possible, for instance, for a system of units designed for control purposes to operate powerful contactors in the immediate vicinity of storage elements, or for busbars carrying several kiloamperes to run only a few metres away.

The resultant power level is thus clearly above that of digital computers, which only have to allow for very small disturbances. It is nevertheless a whole order of magnitude below that of light-current relay controls, and two below that of contactor control systems, which are widely distributed in

automatic power installations. The dimensions of the Brown Boveri electronic installations can be kept so small that a considerable saving in space can be effected compared with conventional contactor controls; further reduction in space serves little purpose, owing to the given size of the power equipment.

Computing Speed

One of the principal differences between the individual ranges is the speed of computing which can be attained. High speed must usually be paid for by high-priced transistors, thus making it essential for the necessary speed for every application to be very carefully investigated and on no account exceeded. Further information may be found in subsequent articles.

As a result, the analogue units of range 1 (power applications) were so designed that the frequency response of the open-loop controller, presuming it is appropriately connected, passes through zero in the region of 3 kc/s. The digital units of the same range have a limit frequency of several kc/s. The term limiting frequency refers to the maximum frequency at which the simplest digital operation, i.e. the change from 0 to 1 or vice versa, can be repeated. For the range 2 (counting applications) and 3 (tele-operation) the limiting frequencies are roughly of the same order, namely 100 and 40 kc/s. The range 4 (computer applications), with 1 Mc/s, has by far the highest limiting frequency.

Power Supply, Climatic Conditions

Even the most versatile system is restricted in its application when abnormal requirements are stipulated regarding the supply or the ambient atmospheric conditions. From economic considerations, for instance, it is not possible to construct all units in such a manner that they can still function at half their normal service voltage or an ambient temperature of 80° C, although in special circumstances it might be desirable, and is certainly technically feasible. On the other hand it would be quite uneconomical to design installations for air-con-

Characteristic values of the ranges

Range				1 Power engineering	2 Counting	3 Tele-operation	4 Computer
Max. repetition frequency				1 kc/s	100 kc/s	20 kc/s	1 Mc/s
Standard signals	Analogue A			± 15 V	—	—	—
	Digital	C	0	0 to − 1·5 V	+ 0·2 to − 0·6 V	appr. − 1·5 V	appr. − 0·5 V
			1	− 15·2 to − 24 V	− 4·2 to − 6 V	appr. − 5 V	appr. − 5 V
		D flank		—	appr. 4 V/0·4 μs	2–4 V/1 μs	1–2 V/0·3 μs
Approx. impedance values		output		0·2/1 kOhm	1 kOhm	1 kOhm	1 kOhm
		input		4/22 kOhm	4·7/22 kOhm	dynamic	dynamic
Supply voltages and tolerances * Analogue units ** Digital units				+ 24 V * + 6 V ** ± 2% 0 V + 24 V ± 2% Mains: + 15/−25%	+ 6 V 0 V − 6 V ± 7·5% − 12 V Mains: + 15/−25%	0 V − 24 V ± 30%	+ 1·5 V 0 V ± 15% − 6 V − 12 V ± 0·2%

ditioned rooms, capable of working reliably at temperatures down to —20° C.

Consequently the various ranges are largely adapted in this respect to the standard conditions in the field of application for which they are visualized. Ranges 1 and 2 must, of course, both fulfil the same severe conditions. Range 3 is less particular as regards atmospheric conditions but, when, supplied from a battery, must be capable of withstanding considerable voltage fluctuation. The stipulations for range 4 are least severe as regards atmospheric conditions. In this case it is permissible to assume that the room in which the equipment is installed will be air-conditioned, if need be. Further information regarding the characteristic data of the various ranges is given in the table above.

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DESIGN PRINCIPLES OF THE BROWN BOVERI ELECTRONIC SYSTEM

621.38

The employment of semiconductor elements and the use of printed circuits offer new possibilities as regards the construction of industrial and commercial equipment. The present article describes the features of a new design principle, which was developed for tasks associated with the "building blocks" of the Brown Boveri electronic system for equipment employed in the spheres of control engineering and information handling.

IN RECENT years two important new developments have become available for the sphere of industrial electronics: transistors and printed circuits. Having undergone considerable improvement, both are now capable of fulfilling very severe conditions and may therefore be made the basis of a fundamental revision of industrial electronics.

But new components and processes also demand new design principles if the products as a whole are to be better and more reliable. The design and circuitry must therefore be planned in close collaboration if the entire system is to be logically organized and able to be employed with economic advantage. To achieve this, elements must be created which, following well contemplated development and rational manufacture, can be combined to form units and installations. These requirements automatically lead to a unit construction principle.

Organization of the Circuitry

Self-contained parts of circuits, which can be employed universally and lead to components of economic size, can be designed as "building blocks". The stipulation that the amount of equipment be reduced to a minimum is frequently fulfilled in analogue techniques, so that the realization of *basic circuits* (amplifiers, impedance analogues, etc.) is justified. If, however, the space occupied by a basic circuit is too small, as is often the case in elements employing digital signals, constructional combination is then carried out for *groups* of basic circuits, resulting in complicated formations, such as counting chains, stores, etc. Employing the electrical elements referred to, it is possible to produce large self-contained circuits which, as *units* within the framework of complete control systems, have definite tasks to perform (controllers, program stores, etc.). Of course, it is sometimes permissible to consider a basic circuit or group of circuits as a unit. The last term to be allocated a specific meaning, referred to all units performing a particular control or information handling task, is an *installation* (speed control or telemetering installation, etc.).

Constructional Organization

From the constructional aspect a universally applicable and reliable design must satisfy the following conditions.

(a) It must be a system of "building blocks"

(b) Dimensions must conform to international standards,

(c) All important connections must be easily accessible in service,

(d) It must be possible to exchange elements quickly in the event of a breakdown,

(e) It must favour natural ventilation (convection), and offer facilities for the incorporation of a means of forced-draught ventilation,

(f) It must have a compact layout,

(g) It must provide facilities for fitting operating and supervisory elements,

(h) Units must be self-supporting, even when installed outside switchboards,

(i) Mechanical protection of built-in elements by the main members during manufacture, storage and transport,

(j) Protection against direct ingress of dust.

The above organization as regards circuitry and the constructional requirements are fulfilled by the new Brown Boveri tiered arrangement, the main features of which are as follows:

The basic circuits and groups of circuits are prepared as mechanically independent units in the form of printed circuits or sub-assemblies. These component sections are joined together by plug or soldered connections in a tier of a rack to form units (Fig. 1). The tiers are then mounted one above the other in the rack, which itself is mounted on hinges in a cabinet. Heavy parts, such as magnetic amplifiers, power packs, etc., or parts carrying heavy currents, e.g. rectifier sets, are mounted on horizontal runners inside the cabinet or placed direct on the floor (Fig. 2).

The dimensions of the entire system are based on the ASA 19-inch standard. Adoption of this design, which is internationally accepted throughout the high-frequency and telecommunications world, offers the advantage that elements produced by outside manufacturers—e.g. oscillographs—can easily be accommodated with the Company's own elements in the same cabinet. The standard stipulates a uniform width for all equipment, namely 19 inches, as well as heights which are whole-number multiples of the basic dimension of $1\frac{3}{4}$ in.

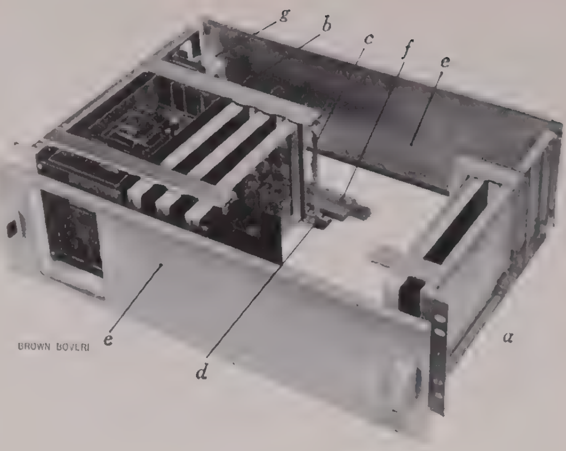

Fig. 1. – Sectional model of a tier

Constructed of standardized parts it carries the printed circuits and sub-assemblies

a = Side section
b = Guide rail
c = Carrier plate
d = Contact spring
e = Cover plate
f = Wiring channel
g = Terminals

The circuit and constructional organization of the Brown Boveri electronic system is summarized in the Table below.

Constructional organization	Circuit organization			
	Basic circuit	Circuit group	Unit	Installation
Printed circuit	×	×		
Sub-assembly		×	×	
Tier			×	
Group of tiers, in pivoted rack			×	×

Printed Circuits

The printed circuits used in the Brown Boveri electronic system are plug-in components in which the conductors for a certain circuit are etched from a layer of copper applied to a thin board of insulating material, and can be used for basic circuits or groups of circuits (Fig. 3) [1, 2].[1] A metal frame holds and guides the plate firmly in the tier, at the same time affording mechanical protection for the built-in

[1] The figures in brackets refer to the bibliography on p. 675.

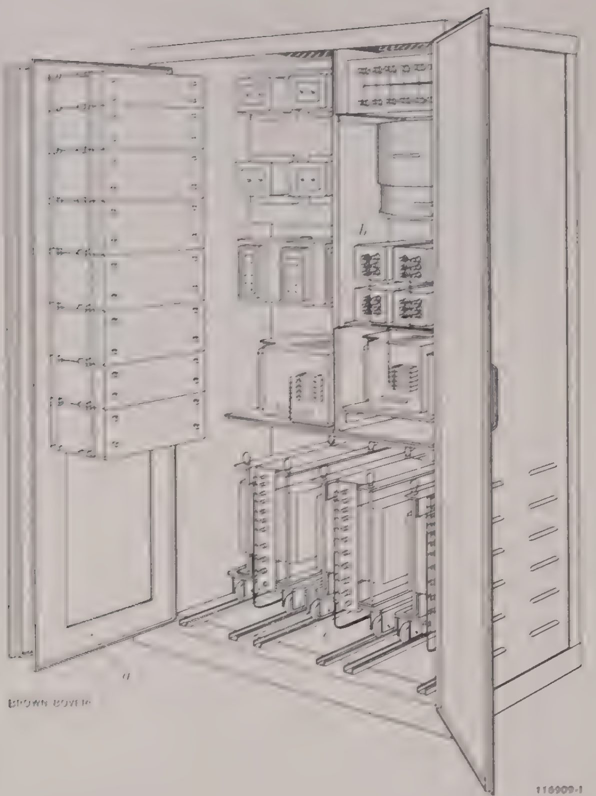

Fig. 2. – Control board

All the main elements of a control system can be accommodated in a single cabinet

a = Hinged frame with input and control units
b = Rear of cabinet with output units
c = Floor of cabinet with standing output units (high-power magnetic amplifiers, transformers, and similar heavy parts).

Fig. 3. – Printed circuit, the smallest "building block" of the Brown Boveri electronic system

designed as plug-in element with gold-plated contact system.

element. The term printed circuit is now commonly used for all circuits produced from metal foils, without stating anything definite about the manner in which it is produced, i.e. by printing or by etching. A description of the process used for producing these circuits would exceed the scope of the present article. It may merely be stated that the printed circuits used in the Brown Boveri electronic system are produced by a photo-etching process in order to obtain the desired accuracy [3, 4].

A decisive factor for the quality of the printed circuit is the base material (carrier with a thin layer of copper foil) [5, 6]. Depending on the particular application, bakelized paper or, more often, reinforced glass fabric bonded with melamine or epoxy resin with standardized thickness of 35 and 70 μ copper foil. Base materials employed in Brown Boveri equipment are first subjected to intensive tests; the main points examined, under different climatic conditions, are as follows:

Mechanical distortion
Suitability for stamping
Resistance to corrosion
Dimensional tolerances
Absorption of moisture
Hardness
Tensile and shear strength
Insulation resistance
Electrical strength
Power factor tan δ
Dielectric constant
Conductor adhesion
Durability of soldered joints
Durability in gold bath

The three latter tests are particularly concerned with the quality of the applied copper foil, for which high durability at elevated temperatures and in the

gold bath are stipulated. Durability at elevated temperatures is essential in order that soldering may be performed rapidly but intensively on the one hand, while, on the other, a constant ambient temperature of 55° C plus the heat dissipated in the conductor can be withstood without damage.

Minimizing stresses during soldering is one of the responsibilities of skilled assembly, whereas the temperature rise in service can be controlled by low specific loading and good natural ventilation. The printed contact system is coated with a layer of gold 6 μ thick with a Brinell hardness of 180–200 kg/mm², thus permitting good contact to be made and a high resistance to wear attained.

The final operation in the manufacture of a printed circuit, after connecting all parts and testing the circuit, is to apply a coat of protective varnish, which fixes the small elements in position, besides affording good protection against harmful atmospheric influences.

Observation of the above points and continually checking them during manufacture have made printed circuits a reliable element of industrial electronics.

Sub-Assemblies

The sub-assemblies in the Brown Boveri electronic system are constructional units suitable for accommodating groups of circuits or units, but which do not fill a complete tier (Fig. 4). A number of them can be combined to form a tier, after separate assembly and testing. As Fig. 4 shows, a sub-assembly can easily contain operating or supervisory elements and contain a number of printed circuits.

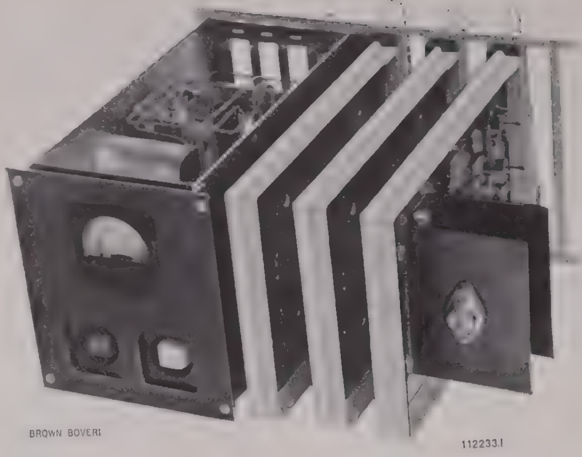

Fig. 4. – Sub-assembly, of standardized dimensions

for incorporation in a tier, suitable for the accommodation of printed circuits, electrical components, also operating and supervisory elements.

Tiers, Groups of Tiers

The tier, on which this design is based, is the element carrying the printed circuits, sub-assemblies, output terminals of the units, and the wiring between individual elements (Fig. 1). As mentioned earlier, the dimensions conform to ASA standards (publication C 83.9) [7].

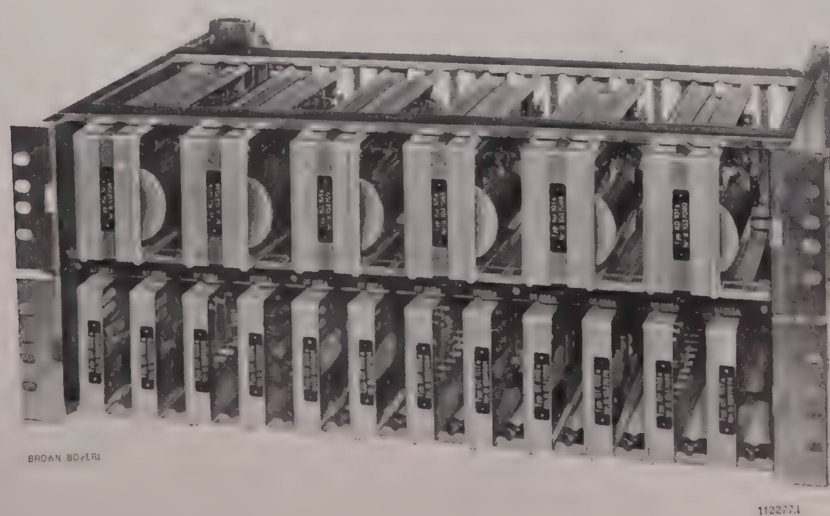

Fig. 5. – Tier equipped with printed circuits

in the tiers printed circuits and sub-assemblies are combined to form units.

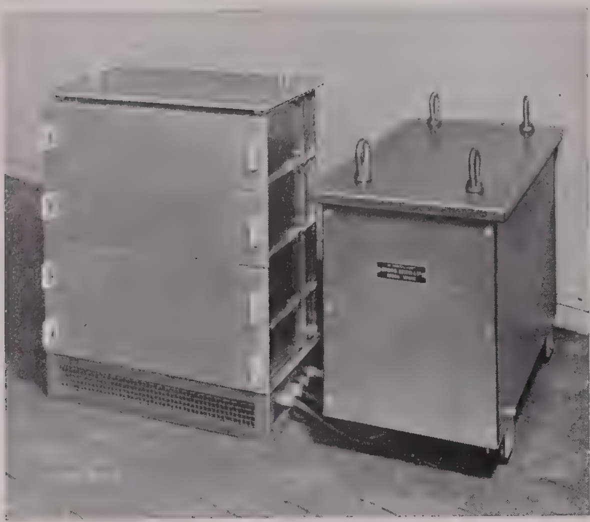

Fig. 6. – A group of self-supporting tiers

The tier-type units are also suitable for installation as separate self-supporting units outside a switchboard (high-power magnetic amplifier with control and rectifier tiers).

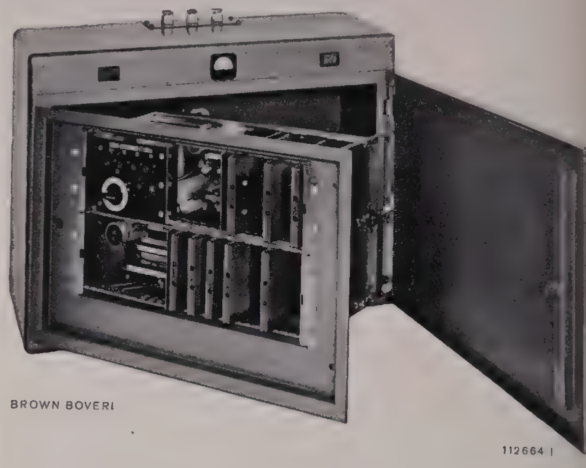

Fig. 8. – Open floor-mounting cabinet with hinged frame

The tier arrangement affords optimum access to terminals and connection points, and allows check measurements to be taken in service.

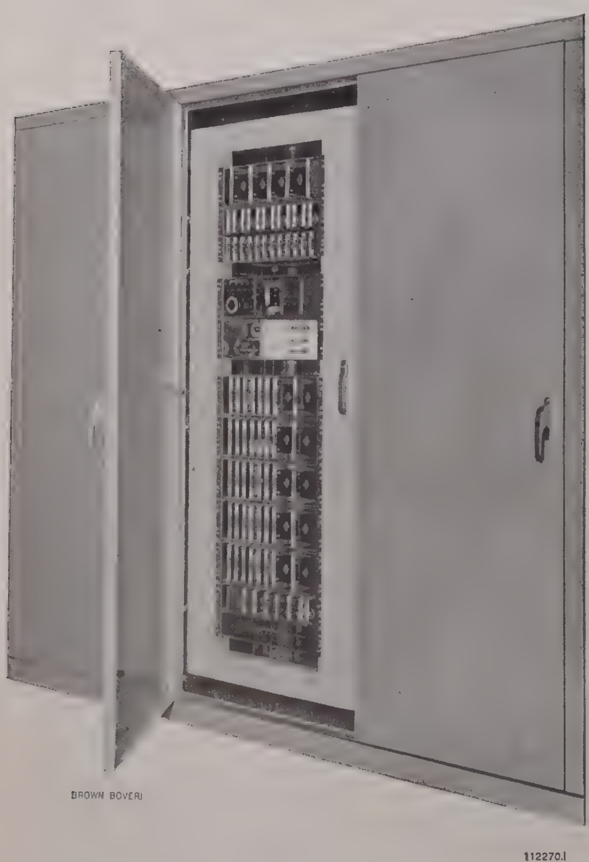

Fig. 7. – Switchboard with control panel and hinged frame

The panel fits into the row of other panels.

The constructional design is as follows: (See Fig. 1.) Two identical side parts *a* are joined together by four guide rails *b* to form a unit. The rails are designed as hollow elements with a slot down one side to accommodate the carrier plates *c*. Inside the rails is a curved contact spring *d* which holds it free from vibration and acts simultaneously as the earth connection. At right angles to it are 24 slots for insertion of printed circuits and sub-assemblies. The wiring is preferably laid in the channel *f*, which was specially designed for the tier system. In this framework the individual printed circuits and sub-assemblies stand like books on a shelf, protected against damage by the side sections. The warm air rises between them unhindered, thus avoiding local stagnation and over-heating. The front and rear of a tier can be closed by covers *e* with a quick-release attachment, thereby creating a chimney which promotes natural convection. For units where the power dissipated is high, a ventilator unit can be incorporated in one of the tiers to produce a forced draught. By bolting several tiers together, they can be combined to form a group which can then accommmodate larger equipment units. Such groups of tiers are usually also mounted in a hinged frame, but they can also be arranged as a self-supporting unit (Fig. 6).

Hinged Frames

The advantages of the Brown Boveri tier arrangement are most evident when the individual tiers are mounted in a hinged frame (Fig. 7). In a switchboard the frame either forms the door itself, or it is situated immediately behind it. With this arrangement all electrical elements are easily accessible from the front in the assembly space of the tiers. When the frame is swung out, the rear of the tiers, or the wiring space, becomes fully accessible, thus greatly facilitating inspection in service (Fig. 8). For small installations a small wall-mounting cabinet is available in two sizes (Fig. 9).

Summary

In conclusion it may be claimed that, parallel to the creation of a uniform system of equipment, the Brown Boveri electronic system also produced a new constructional principle. With the Brown Boveri tier arrangement, equipment for control and information handling is all designed on the same lines and fulfils the stipulations regarding reliability and economy referred to in the introduction.

(KME) T. Ernst

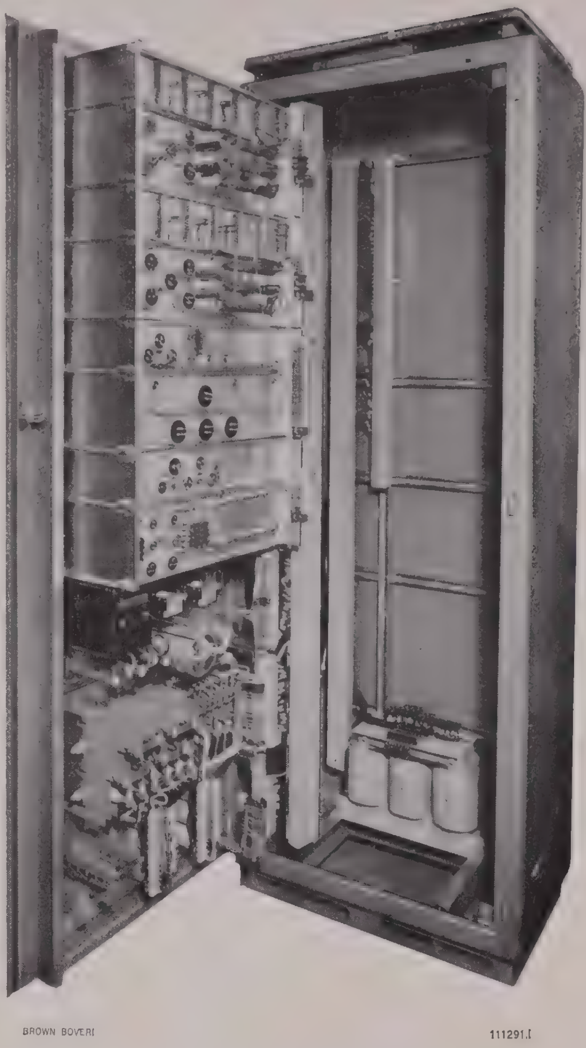

Fig. 9. – Small cabinet with hinged frame

for control systems of limited extent, two sizes of wall-mounting cabinets of this kind are available.

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THE BROWN BOVERI ELECTRONIC SYSTEM—CLOSED-LOOP CONTROL

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The increasing demand for automatically controlled installations led to the creation of a range of closed-loop control equipment which, within the scope of the Brown Boveri electronic system, is designed according to unit construction principles and with which it is possible to solve the majority of the problems encountered in automatic control. The present article is devoted to the fundamentals of the series of units. Although the main stress is on analogue units, these can be combined with the digital elements of other ranges if necessary.

A CLOSED-LOOP control system is based on the following units, which on their own exert integral functions.

The *input units* make available the values measured on the loop (control quantities, disturbances) and the reference input values. They determine the state of the installation to be controlled, as well as commands introduced from outside. It is the task of the input units to convert all kinds of input quantities into uniform signals, which are passed on to the control units for further processing.

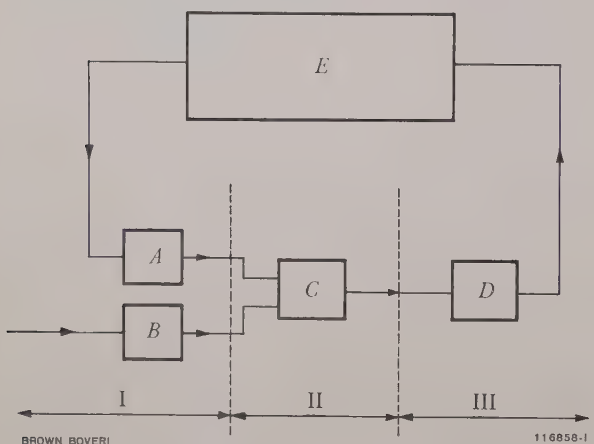

Fig. 1. – The simple closed-loop control circuit with its basic elements

I = Input units
II = Control units
III = Output units
A = Input unit for controlled variable
B = Input unit for reference input value
C = Control unit
D = Correcting unit
E = Controlled object

In this case C consists only of a controller.

The *control units* convert the input quantities into a correcting condition, and in addition to taking into account the actual response of the controller, they also make allowances for other relationships and rules which have to be obeyed. In a simple control system there may, for instance, be a controller with a proportional-integral-derivative (PID) action, which processes the information received—in this case a reference input and a variable control quantity—in such a manner that the output quantity communicated to the correcting unit is able to regulate the difference between these two values to zero. Here the sole task of the control units is to compare the information received, convert it dynamically and amplify it (Fig. 1). More complicated control tasks frequently demand a more complex arrangement of control units. In addition to containing a number of elements having a controller action, these also effect additional relationships, such as the control of a main variable being overridden by a limitation, which keeps a further variable in certain limits, or the mutual distribution of commands to different correcting units which act on a control circuit at different points according to different rules (Fig. 2).

The task of the *output units* is to convert the correcting condition or output into a form in which it can take effect on the control circuit. They amplify the values emitted by the control units to the power required at the point of action and, in some cases, undertake conversion of the signal, e.g. into grid-voltage pulses of varying phase angle for the control of rectifiers.

Standardized signals enabling these different units to be adapted to one another afford generous facilities for the combination of the various kinds of input, control and output units. Thus, with a restricted number of units, it is possible to solve a wide variety of tasks in many different fields of application.

In the majority of practical applications analogue methods lead to the most economical solution. The much larger outlay involved with digital methods only justifies their employment nowadays for control purposes in special cases with very exacting requirements. This article will therefore be confined to analogue control techniques.

In Brown Boveri electronic equipment used for control purposes, a d.c. voltage is employed as standardized signal. Within the specified limits this voltage can assume any value and vary analogously with the value it is supposed to represent. It is therefore known as an analogue signal (abbreviated to A signal). In determining the limits for the A signal the following main points governed the choice: The maximum voltage is on the one hand dependent upon the available components, especially the transistors, which impose an upper economical limit for the magnitude of the signal. On the other hand, larger signal values yield more reliable and accurate control. The A signal was therefore standardized in such a manner that it corresponds to the technical and economic optimum for most of the systems which have to be realized. Its maxima were set at $\pm$ 15 V. By using both polarities it is easy to deal symmetrically with physical quantities of varying sign, such as speed, acceleration, current, voltage, power, and so on. This exerts an advantageous influence, both with regard to simplifying the design of the input units and processing the signal in the control and output units.

However, it is only possible to take full advantage of a d.c. voltage when complex control systems can also be constructed without galvanic separation. For this reason all standardized signals, which extend from the output of the input units up to the input into the correcting units are combined with one another, without further means of assistance.

Special care was taken to make the units independent of mains voltage fluctuation. The control units operate at a low power level and are fed with stabilized d.c. voltages. For the input and output units, having regard to the higher power usually required, it is no longer economically justifiable to stabilize the supply, so that in this case mains voltage fluctuations are rendered ineffectual by suitable arrangement of the electrical circuits. The independence of all units from the mains voltage allows high-grade control systems to be realized, even in unsteady power networks, such as are frequently encountered in industrial plants.

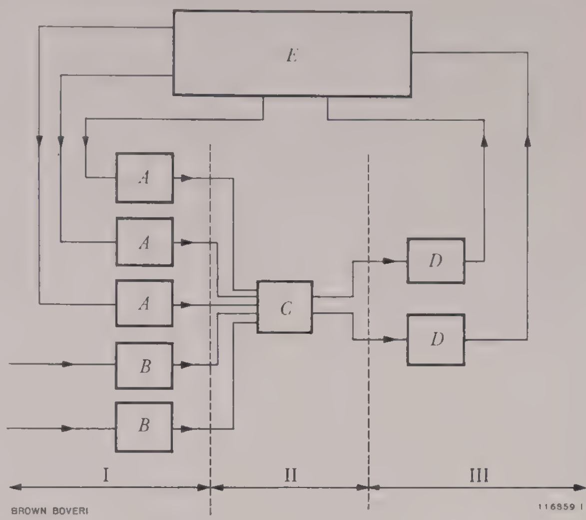

Fig. 2. – Example of a control circuit with several controlled variables and reference inputs, and with two control points

I = Input units
II = Control units
III = Output units
A = Input units for controlled variables
B = Input units for reference input values
C = Control unit
D = Correcting units
E = Controlled object

In this case the control unit, in addition to performing the functions of a controller, also has to combine the variables and reference inputs, and to distribute the correcting condition in accordance with the requirements of the controlled object.

Input Units

The quantities required for the operation of a control system (controlled variable, reference input, disturbance) are converted into standardized signals by the input units. As already explained, except for a few special cases which will not be dealt with

here, these signals are laid down as $\pm$ 15 V d.c. The quantities which have to be converted, e.g. speed, direct current, temperature, cause an electrical quantity to vary in accordance with known laws, this quantity being either the desired voltage or a quantity which can easily be converted into it. For instance, a tachogenerator converts the speed of a shaft into a voltage with the aid of Faraday's law of induction

$$u = c\,\Phi\,n$$

where

u = induced voltage
Φ = exciting flux
n = speed of rotation
c = a constant.

In a commutator machine this is a d.c. voltage, otherwise it can be converted into one by diodes.

For certain electrical quantities it would be very simple indeed to obtain input values by a direct route, e.g. direct current obtained by means of a shunt. For reasons of reliability, flexible layout of the control circuits and avoidance of disturbance, however, d.c. transformers are employed. They are not only used to convert the measurand to the standardized signal, but also to separate the control circuits galvanically from the main circuit, whose power level may be in the kW or MW range.

Table I lists the most important input units for control tasks. Combined quantities are only determined in the control units in many cases; for example the electric power is calculated by multiplying voltage and current.

A special position is occupied by the reference input as soon as a program store, such as a punched-card system, is employed.[1] Here the technique of closed and open-loop control become very closely associated. The connection between digital programming with C (code) signals and the control systems operating with A signals is established by a digital-to-analogue converter, which combines a stepped series of C signals to obtain the desired A signal. Its basic element, the C-A converter, is included in Table I, although it may equally well be classed with the control units. The program stores are dealt with in a subsequent article.

Control Units

The operations which the control units have to perform may be reduced to a number of basic functions, the most important of which are:

- amplification
- conversion in function of time (dynamic response)
- linear processing of signals (mixing)
- non-linear processing of signals (limiting, formation of threshold values, selection from several signals, multiplication, etc.)

[1] See page 705 of this issue.

TABLE I

Input units for use with electronic control systems

Unit	Application or range
D.C. transformer	$\pm$ 5 to 7000 A
D.C. voltage transformer	$\pm$ 100 to 2000 V
Discriminator	For true-to-phase conversion of voltages from a.c. into d.c. for connection to normal instrument transformers and synchros
Tacho-generator	For measuring speeds: range $\frac{1\ \mathrm{V}}{\mathrm{rev/min}}$ to $\frac{60\ \mathrm{V}}{1000\ \mathrm{rev/min}}$
Radiation pyrometer	400–1500 °C
Digital-to-analogue converter	Combination of reference input values from individual commands from programming devices

TABLE II

The basic control units used in electronic control systems

Type	Unit	Number of circuits	Task
QT 002a	D.C. push-pull amplifier	1	Signal, summation, differential and integrating amplifier
RZ 401a	Feedback unit	1	Adjustment of response
RZ 901a	Supplementary capacitor	1	For feedback
RZ 402a	A signal mixer	1	Addition of signals for input to push-pull amplifier
BD 101a	A signal limiter	2	Limitation of signals
PT 005a	Impedance converter	1	Raising the load capacity of signals
PT 006a	Max. value amplifier	1	Transmitting the largest of four signals
PT 007a	Min. value amplifier	1	Transmitting the smallest of four signals
UT 011a	Digital-to-analogue converter	1	The input signals 0 and 1 represent constant output voltages of + 15 V and — 15 V
UT 015a	Analogue-to-digital converter	1	When the input voltage passes through 0, the output changes from 0 to 1 and vice versa
FD 101a	Function generator	1	Transmitting $u_A = f(u_E)$
ET 001a	Multiplier	1	Multiplication

– matching the control system operating with continuous A signal to the C signals of the digital system.

Table II lists the functional elements most frequently encountered.

A full description of all these units would exceed the scope of this article. Therefore, as typical examples, the most extensive and the simplest functional elements are picked out and described in detail. These are the d.c. push-pull amplifier and the limiter.

The *d.c. push-pull amplifier* forms the basis of analogue signal-processing systems in its capacity as summation, differential or integrating amplifier. Its severely simplified circuit diagram is shown in Fig. 3. It operates on the differential amplifier

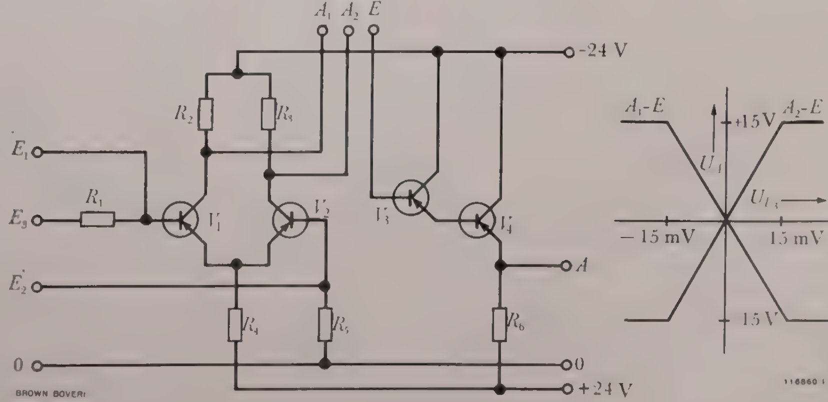

Fig. 3. – Severely simplified circuit diagram of the d.c. push-pull amplifier, showing the characteristics

E = Inputs
A = Outputs
V = Transistors
R = Resistors

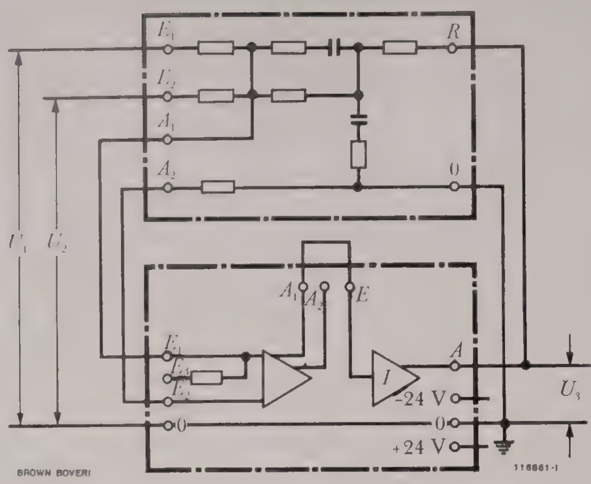

Fig. 4. – D.C. push-pull amplifier with supplementary timing network

U_1 = Desired value
U_2 = Actual or momentary value
U_3 = Correcting condition
E = Inputs
A = Outputs
R = Feedback input
I = Impedance converter

principle and has a continuous zero bar, to which the input and output voltages are referred.

The characteristic factor of this amplifier is the relationship between the output voltage and the input current, whereas the voltage amplification normally quoted is influenced by the input resistance. This is made up of the dynamic resistances between the base and emitter of the transistors V_1 and V_2, and the base bias resistances, which may be freely chosen within predetermined limits. When the amplifier is driven through the input E_3 the two bias resistors R_1 and R_5 are 22 kΩ each. In order to take into account the usual application as asymmetrically driven control amplifier, the two amplifier inputs (E_1, E_2) are brought out direct. The mixing resistors for the desired and momentary values, and possibly the feedback, are then connected to E_1, while by means of a balancing resistor between E_2 and the zero bar the built-in base bias resistor R_5 can be balanced in such a way that it equals the resultant mixing resistance. The equality of the base bias resistors of the two inputs so obtained is essential for accurate control.

The push-pull outputs A_1 and A_2 of the amplifier have a high impedance and may only be loaded when impedance converters are connected between them. For this an impedance converter fitted to the same printed circuit is used. One input E may be connected with either the output A_1 or A_2, thereby allowing any desired direction of action of the input and output signals to be obtained. If both outputs are needed, the additional impedance converter required has to be added separately.

The behaviour with respect to time (response) needed for control purposes is varied by equipping the amplifier with *RC* networks (Fig. 4). The frequency response of the amplifier itself is compensated, enabling it to operate stably with any negative feedback, regardless of its impedance. As a result of using silicon transistors and careful dimensioning the push-pull amplifier has excellent technical properties.

The technical data of the d.c. push-pull amplifier are as follows:

Output voltage / Input current	$>$	45 MΩ
Voltage amplification when driven via E_3	$>$	60 db
Limiting frequency ($\Delta V = -3$dB)		1 kc/s
Range of input current	$\pm$	0·33 μA
Admissible overload (E_3)	$\pm$	60 V
Thermal drift (mean value)		25 nA/°C
Output voltage	$\pm$	15 V
Load capacity	$\pm$	5 mA
Internal resistance at output terminal	$<$	100 Ω
Supply voltage	$\pm$	24 V
Consumption		2·4 W

The circuit diagram of the simplest functional element, the *limiter*, is shown in Fig. 5. Its task is to limit signals to a positive and a negative reference voltage applied from outside. This limitation is required, for instance for the output voltage of a push-pull amplifier, when the latter is used as desired value for a subsequent control circuit, and its momentary value must not exceed certain limits. If the magnitude of the input voltage exceeds the momentary reference voltage U_R, the diode, which had remained blocked until then, becomes conducting and, as a result of its very low internal resistance, keeps the output voltage down to the value of the reference voltage.

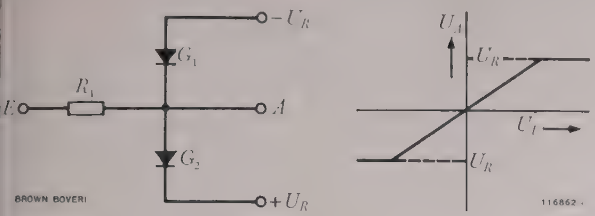

Fig. 5. – Circuit diagram of limiter, with characteristics

E = Input G = Diodes
A = Output U_R = Limitation voltages
R_1 = Resistor

Technical data of the limiter:

Voltage amplification $\dfrac{R_L}{R_L + 1\,\text{k}\Omega}$ (R = load resistance)

Admissible reference voltage $11{\cdot}5\ \text{V} \leqslant |U_R| \leqslant 24\ \text{V}$

Admissible load resistance $3{\cdot}2\ \text{k}\Omega$

Output Units

The output units of the Brown Boveri electronic system, provided they have a continuous action, have evolved out of the correcting units which have been used for many years for electrical control systems, namely the thyratron and transductor power stages and the grid control sets for mercury-arc rectifiers. These units were adapted to the standardized signals by transistor input stages. New developments in components have been taken into account and power stages based on semiconductors added. Thus for the entire power range—from the order of watts to megawatts—an appropriate choice of output units is available, with which, in conjunction with the other units of the Brown Boveri electronic system, as well as classical electrical machines and equipment, the widest variety of control tasks can be performed.

A feature common to all output units is that the effect of mains voltage and load fluctuation is almost completely eliminated and the characteristics possess good linearity (Fig. 6). The settling times have been considerably reduced, for example with two-stage three-phase power transductors they are less than 20 ms. Rectifiers, thyratrons and controlled silicon rectifiers have been equipped with instantaneous control sets, enabling settling times to be obtained with theoretical minimum values of fractions of a cycle given by the number of phases.

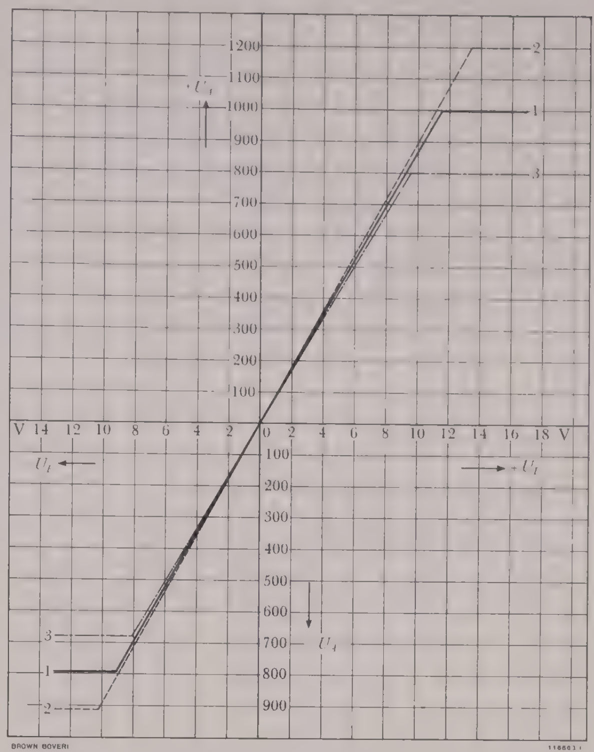

Fig. 6. – Characteristics of a mercury-arc rectifier with transistorized grid control set, showing the effect of varying mains voltage

U_E = Input voltage to control set
U_A = Output voltage of rectifier
1 = Characteristic at rated voltage
2 = Characteristic at 20 % over-voltage
3 = Characteristic at 20 % under-voltage

Being unaffected by changes in the mains voltage, this set can be employed in unsteady networks.

The list of output units by no means represents the final stage of development. Output units have to be adapted to the particular installation being controlled and thus continually have to conform to new requirements.

The units of the Brown Boveri electronic system used for closed-loop control, like those employed for other purposes,[2] are designed according to a unit construction principle.[3] By combination with groups of units from other classes, it is also possible to produce control systems with a harmonic overall arrangement.

(KME)

R. Zwicky
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[2] See pages 682, 697 and 701 of this issue.
[3] See page 670.

THE BROWN BOVERI ELECTRONIC SYSTEM — OPEN-LOOP CONTROL

621-523.8

Nowadays, for open-loop control, transistor and diode circuits are employed which are capable of complying with the increasingly severe demands made regarding reliability and operating speed. Within the scope of the Brown Boveri electronic system a complete series of digital elements is available in the power engineering and counting ranges, expressly designed to meet the needs of open-loop control in power systems and industrial installations. The article first deals in general terms with the problems encountered in these spheres, and with the means available for their solution. The two ranges of elements are subsequently described separately in greater detail.

Control Terminology

OPEN-LOOP CONTROL, in the widest interpretation, is influencing one physical quantity by another, independent quantity, a principle widely employed in engineering. The very simple action of switching on a lamp, or the automatic machining of a workpiece according to a program carried on a punched card are both typical examples of open-loop control. These two examples also help to demonstrate the wide span of problems which may be encountered, both as regards difficulty and complexity. Open-loop control systems—in which a desired effect is achieved by the action of one or more elements in a *forward* direction only—represent by far the minority of the possible cases. In the majority of cases states and quantities are communicated back to the control system, thereby closing the loop.[1]

[1] See preceding article on page 676.

Organization of Control Systems

If the extraordinarily wide range of difficulty in the tasks imposed on the different kinds of control system, as indicated by the above example, is to be conveniently subdivided, the following graduation may be made, according to the complexity of the proposed solution.

1. Direct Control

These are systems in which the command is executed at once unless it is prevented for some reason or other. This kind of prevention is necessary, to avoid inadmissible operating conditions, and is effected by an interlock. In direct control a command which is prevented from being executed remains ineffective, that is to say, it must be repeated when the interlock is removed. An example is the control of a switchgear installation, where a command to open or close a circuit-breaker or isolating switch is only effective if the action is permissible with respect to the position of the other switches.

2. Sequential Control

These are systems in which a number of actions are executed successively in a pre-determined sequence when a command is given. The sequence may be controlled by set timing mechanisms or by acknowledgement signals from the process itself. The combination of these alternatives is also feasible. An example of sequential control is the control of a

simple lift. When the button is pressed, the brake is released, the motor started; on attaining a certain position the motor is switched to low speed; when the lift approaches the final position the motor is switched off and the brake applied. One may also speak of sequential control when a command once given is stored until such time as its execution is permissible and it is then automatically carried out.

3. Program Control

In program control systems the sequence of the various actions is governed by a program which may either be preset or carried by a suitable medium (punched card or tape). This form of control is employed when a process of one particular kind has to be frequently repeated, but where details of the sequence may have to be changed periodically. The equipment for introduction of the program becomes increasingly extensive and costly, the more frequently the program has to be changed, and the more details it contains. In simple cases crossbar selectors are used, on which the program is preset by inserting plugs at definite points. For frequent change with only a small amount of detail punched cards may be used; when the amount of data to be programmed is large, punched tape is preferable.

4. Numerical Control

In this form of control the result is fed into the machine in numerical form, using a digital method of representing the desired quantity. It is used because the storage of commands in digital form is much simpler, or because the desired accuracy cannot be attained with analogue means. In most cases a system of numerical control also involves one or more closed loops. If the digital method of representation is only employed in that part which is used for storing the commands and for the input of the desired quantities, this may be referred to as a digital-program control system. A feature of digital closed-loop control is that the comparison between the desired and momentary value of the controlled variable is performed by digital methods. An example of numerical control is positioning on a drilling machine, where the positions at which a hole has to be drilled can be defined accurate to several places of decimals by introduction of the x and y coordinates. The machine moves automatically to the set position and drills the hole without the machinist having to check that the correct position has in fact been reached.

Requirements of Industrial Control

In the course of automation of industrial processes the requirements imposed on the control equipment with regard to dependability, speed and complexity have become increasingly severe. With the automation of larger sections of manufacturing processes it is necessary to determine more and more individual data and their relations. The number of separate items of equipment and the frequency of their operation grow accordingly. Having regard to the space occupied, the maintenance required, and the life which may be expected, it may be impossible in many cases for complex control systems to be realized with contactors, even though this might still be feasible from the speed aspect. In other cases the solution of an automation problem leads to speeds which are unattainable with relay or contactor circuits. This is particularly true of systems controlling mercury-arc rectifiers, or numerical control systems. For instance, for the control of reversible machines fed from rectifiers, it is necessary for one rectifier set to be switched off and another on up to 50 times per second. A digital system of positioning control, which has to work to an accuracy of a hundredth of a millimetre, but which must permit a feed speed of 10 m/min, needs a counting rate of 20 kc/s. For such tasks the power engineering and counting ranges of the Brown Boveri electronic system were created. The transistor circuits used in these fulfil all the requirements with regard to reliability and speed encountered in these fields. Their design is easily interchanged, compact printed circuits facilitate combination which, from

the electrical aspect, is assured by the use of a uniform supply voltage and standardized signals, referred to a zero line going right through. This zero line is insulated from the power supply and is generally earthed at one point in the installation. Thus the earthed parts of the chassis and screens cannot introduce any capacitive noise voltages.

The employment of these units in conjunction with industrial installations or machines makes it essential for them to be insensitive to noise voltages introduced from such machines. This is particularly true of units of the power engineering range which establish the direct connection between the electrical machines and equipment. To attain this goal this range dispenses with maximum speed where necessary. In the counting range, the units of which only establish contact with the machine via special sensors or detectors, it was possible to somewhat reduce the requirements regarding insensitivity to noise voltages in order that the necessary high speed could be attained. A feature common to both ranges is that both can be expected to be installed where there is a powerful supply system available and that they will be able to draw their power through appropriate power packs. Also they can expect to be installed indoors, which gives rise to certain requirements regarding the ambient temperature. For these power packs and all units connected directly to the alternating supply, the following figures apply to the supply voltage:

Frequency: 48 — 52 c/s; for specially marked units up to 63 c/s

Voltage: 220 V, single-phase, 380 V three-phase; tolerances $+10\%$ to -15% sustained, to maintain the properties of the unit; $+20\%$ to -25% for 1 min, unit safe from damage

The following temperatures are admissible in the immediate vicinity of the unit:

$+5$ to $+55$ °C to maintain properties of the unit,

-25 to $+5$ °C the unit still functions properly but the quality may deteriorate.

The temperature will probably only drop below the lower limit of 5 °C in indoor installations when rooms have remained unheated for a long time, during which time the equipment was switched off. As soon as they are switched on the limit is exceeded due to the heat generated. The second group of figures indicates that the units will still function properly during this time.

Means of Solving the Problems of Electronic Control

The open-circuit control units of the Brown Boveri electronic system employ circuits with specially selected and tested transistors and diodes for the solution of their problems. The subdivision into input units, control units and output units, together with the utilization of standardized signals in the control units makes the use of only a relatively small number of units possible. The simplest of these units contain basic circuits, whose main task is to effect the logical relation between different signals, storage and timing. These are augmented by circuits which convert or shape signals. Other units contain combinations of basic circuits for more difficult functions, such as counting, comparison, encoding and decoding.

Each of these functions can be performed by a variety of circuits, from which the most convenient must be selected. This question will now be discussed in rather general terms, details of the power engineering and counting ranges of the Brown Boveri electronic system being dealt with in later sections of this article.

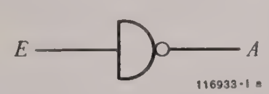
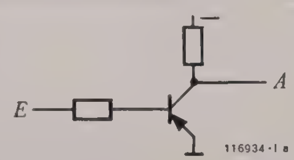
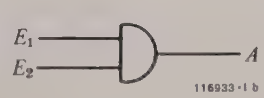
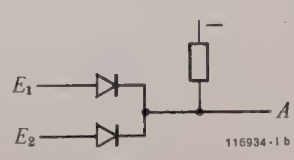
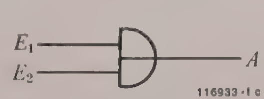
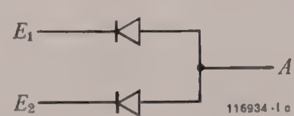
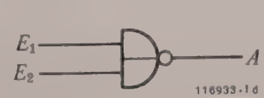
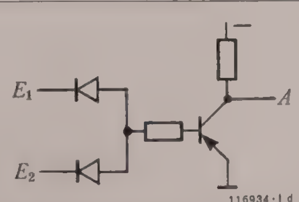
A logical operation is one in which several quantities, capable of assuming different states, are related to produce a single new quantity, which can also assume different states, in accordance with a stipulated rule. If each quantity can, or is only permitted to assume two states, it is customary to refer to binary logic. This is the easiest form to realize technically. Control systems employing contactors or relays, as well as the transistor and diode circuits employed in the Brown Boveri electronic system for open-circuit control realize a binary logic. The two

states, which in relays are attracted or unattracted, in contactors closed or open, are given in transistor circuits by a voltage signal, known as the C signal, which is either negative in a definite range—in which case it represents the value '1'—or is in the region of zero and then represents the value '0'. The voltage ranges for '1' and '0' are standardized throughout the ranges and exactly defined, in every case being separated by an ample "forbidden region", which must be traversed at a definite minimum speed, stipulated for each range.

The interconnection of relay contacts, as a combination, can open or close the circuit, according to whether the individual contacts in a particular combination are open or closed. Likewise, the task of a transistor or diode circuit which performs a logical operation, and is known as a gate, is to form from several input C signals a single C output signal, representing 0 or 1, depending on the combination of 0 and 1 in which the input signals arrive.

The rules governing such relations are extremely varied though. With only 4 input signals there are 65536 possible different relations. With 10 input signals the number has grown to about 10^{300}. Hence it would be quite impossible to design a gate for every one of these possible combinations. Fortunately, however, the complicated relations can be produced from a small number of simpler ones. For the main simpler relations Table I lists the names, the relationship between the input and output values (in the form of a truth table), a symbol describing complex operations in a signal flow diagram, and finally realization of the relationship by a transistor and diode circuit.

TABLE I

No.	Designation	Truth table	Symbol	Circuit
1	Inverter	$\begin{array}{c\|c} E & A \\ \hline 0 & 1 \\ 1 & 0 \end{array}$		
2	AND gate	$\begin{array}{cc\|c} E_1 & E_2 & A \\ \hline 0 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \end{array}$		
3	OR gate	$\begin{array}{cc\|c} E_1 & E_2 & A \\ \hline 0 & 0 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{array}$		
4	NOR gate	$\begin{array}{cc\|c} E_1 & E_2 & A \\ \hline 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \end{array}$		

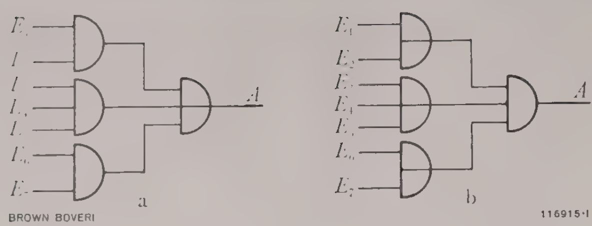


Fig. 1. – Structure of all possible logical operations

a: Disjunction of conjunctions (OR from AND relations)
b: Conjunction of disjunctions (AND from OR relations)

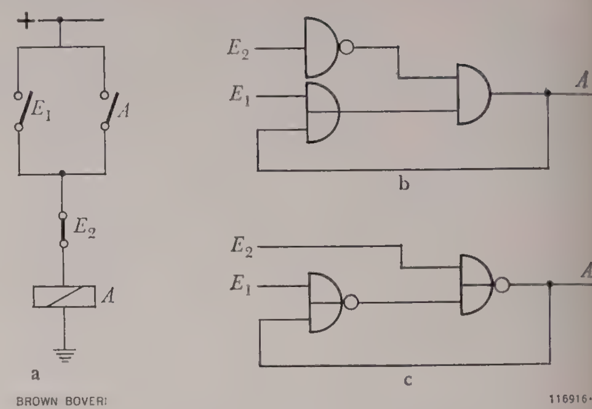


Fig. 2. – Realization of a storing circuit with relays and with transistor-diode gates

a: Relay circuit
b: Associated signal flow diagram
c: Realization with NOR gate

For notation see text.

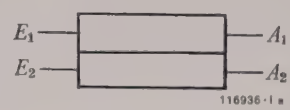
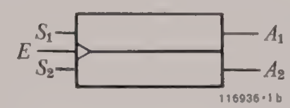
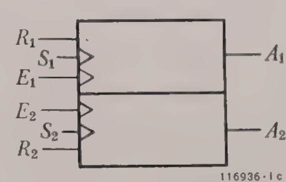
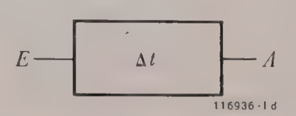
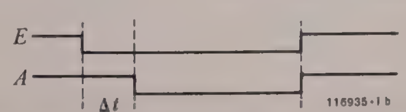
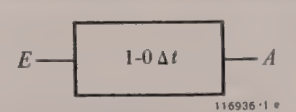
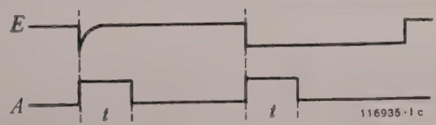
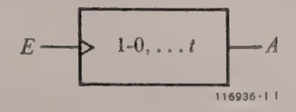
The first logical operation in the Table is inversion (negation). The inversion amplifier (commonly called inverter) produces a 0 at its output when a 1 is applied to its input, and vice versa.

The gate circuits listed in the Table are shown for two inputs. They can, however, be extended to cover any number of inputs. The AND gate only produces a 1 when a 1 is applied to all its inputs; the OR gate always produces a 1 when a 1 is applied to at least one of its inputs. The NOR gate only produces a 1 when none of its inputs has a 1. It can now be proved that even the most complex logical relations between a number of inputs can be equally realized either by a number of AND gates whose outputs are applied to a single OR gate, or by a number of OR gates whose outputs are applied to a single AND gate [1].[1] A prerequisite condition for this is merely that, for feeding the inputs, not only must the actual values be available, but also their inverse (negated) values. Thus all relations can be realized by combinations of gates having the structure a or b in Fig. 1. Then it is merely a question of economy, which is preferred. It is possible to carry simplification a stage further. For instance, in the case b, both the OR gate and the AND gate can be replaced by the same type of NOR gate without changing the result A. Since the NOR gate, utilizing only one input, can also be used as an inverter, it is permissible to claim that all logical relations can be formed solely with NOR gates. Whether this can be justified economically depends on factors like prices of transistors, or the ability to combine basic circuits to form units, which are different in each range.

[1] The figures in brackets refer to the bibliography on p. 696.

With the gates referred to so far it is possible to solve all problems which were classed as direct controls at the beginning of this article. For sequential and program controls it is necessary to provide additional storing elements and timing circuits. Storing circuits can be produced by combining gates, but this demands a certain amount of care. If, as is usual in most cases, storage involves the maintenance of a certain current distribution in the circuit, it may easily be shown that such storage is only possible with the aid of amplification. Thus, for instance, the relay circuit in Fig. 2a can be converted formally into the combination of logic elements shown in Fig. 2b. If the individual units are realized as indicated in the example in Table I, an input signal at E_1 cannot maintain itself because there is no amplification in the circuit closed by the feedback. On the other hand, the conversion shown in Fig. 2c, with a combination of two NOR gates, is perfectly feasible because this type of gate possesses its own means of amplification. The relay circuit in a, however, differs noticeably from the gate circuit c. If the inputs E_1 and E_2 are applied simultaneously, the relay falls back, or the signal A is 0. If the application of E_1 and E_2 ceases at the same time, the relay is sure not to pick up, owing to its retarded action. If, on the other hand, the input signal of circuit c

TABLE II

No.	Designation	Logic operation	Symbol
1	Binary store	E_1 E_2 | A_1 A_2 1 1 | 0 0 1 0 | 1 0 0 1 | 0 1 0 0 to: { 1 0 | 1 0 0 1 | 0 1 1 1 | { indefinite 0 1 or 1 0	
2	Binary counter	*Setting:* $S_1 = D^1$* or $S_1 = 1$ at $S_2 = 0$ compels $A_2 = 0$ and $A_1 = 1$. $S_1 = 0$ after $S_1 = 1$ does not change state. Same behaviour as if subscripts exchanged. *Counting:* $E = D^0$ or $E = 0$ after $E = 1$ changes preceding state of outputs. $E = 1$ after $E = 0$ does not change state.	
3	Binary stage	*Setting, storage:* $S_1 = D^0$ or $E_1 = 0$ after $E_1 = 1$, at $E_2 = 0$ compels $A_1 = 1$ and $A_2 = 0$ $E_1 = 1$ after $E_1 = 0$ does not change state. *Conditional setting:* $S_1 = D^0$ or $S_1 = 0$ after $S_1 = 1$ compels $A_1 = 1$ and $A_2 = 0$, provided R_1 was brought to zero a short time before. $S_1 = 1$ after $S_1 = 0$ does not change state. *Counting:* The change from 1–0 of a C signal or a D^0 signal at the connected inputs E_1 and E_2 changes the preceding state. The change from 0–1 has no effect. Same behaviour with subscripts exchanged.	
4	C retarder		
5	1–0 retarder		
6	One-shot multivibrator		

* D^0 and D^1 are the signals obtained by differentiating the changes of the C signal from 0–1 and 1–0, respectively.

changes at E_1 and E_2 simultaneously from 1 to 0, the result is indefinite. For a brief instant both NOR gates have a 0 at both inputs and the outcome now depends on which of the two is the first to provide a 1 at its output. Since both gates are identical, the result of this "race" is uncertain.

For these and other reasons it is preferable to have storage circuits available, which possess definite properties and which can also be symbolized in the signal flow diagram. The designation, logic and symbols for such basic circuits are listed in Table 2.

Under the heading of sequential control, earlier in this article, it was pointed out that operations may be controlled with respect to time. For this purpose relay circuits employ the relays with retarded pick-up or fall-back, or time-lag relays. In electronics the circuit corresponding to a relay with retarded pick-up is one in which a change from 0 to 1 is retarded, whereas the change from 1 to 0 is passed on without delay. Sometimes electronic circuits are required in which the change has to be equally retarded in both directions. All these circuits will be referred to as retarders, their special logic being indicated by a suffix.

A property of time-lag relays is that they keep one or more contacts closed for a preset fixed or variable time as soon as they receive an appropriate starting pulse. In electronic controls appropriate circuits are employed, which provide an output signal 1 for a fixed or variable time, if they receive a starting pulse in the form of a 0–1 or 1–0 change at the input. The designations, logic and symbols of such timing circuits are listed in Table II.

Organization in Ranges

The conditions imposed on the speed of the elements by numerical controls are considerably more exacting than in other control systems. The latter, on the other hand, demand greater insensitivity to noise voltages and flexibility in combining the basic logic circuits. For these reasons it proved preferable to cover the whole of this field with two ranges. Thus an optimum economic solution could be aimed at in each of these ranges. The different requirements necessitated different supply and signal voltages, but the transition from range 1 (power engineering) to range 2 (counting) is quite easily effected by connecting a signal converter in between. From the construction aspect there is no difference between the two ranges.

Power Engineering Range 1

a. Special requirements

Range 1, in addition to containing units for open-loop control, also contains the units specifically intended for analogue closed-loop control, which have to operate in close relationship with one another. For instance, commands from the open loop have to be converted into desired values in an analogue closed loop; on the other hand, definite commands must be given when a quantity represented by an analogue signal becomes larger or smaller than a specified value. Since the signal voltage was made as high as possible for the analogue part, having regard to the accuracy, and as far as the available transistors permit, a supply voltage of $\pm$ 24 V was chosen. On the negative (power) side the digital part uses the same supply voltage of — 24 V. In addition it requires a further supply voltage of + 6 V in order to be able to block transistors in the given temperature range.

With these stipulations it was an easy matter to create for the transition between the analogue and the digital parts signal converters such as the analogue-to-digital converter which, from an A signal, produces a C signal, which is 1 when the A signal is in a certain region, e.g. positive. In contrast, digital-to-analogue signal converters emit an A signal of two different, but clearly defined values, e.g. + 15 V and — 15 V, according to whether the input signal is 1 or 0. Further details regarding the digital signals are given in the Table on page 669.

Sequential and program controls demand appreciable flexibility as regards ability to combine the

basic circuits. The individual signals are utilized as input signals for other circuits in a large number of different ways. In order to achieve maximum versatility it would be desirable to aim at attaining maximum possible load capacity in the individual units. With due regard to price, the units of the Brown Boveri power engineering range of electronic units were so designed that each is capable of carrying the load of 5 other units connected to it, which ought to afford sufficient flexibility of combination. In those cases where this number is not adequate, a signal amplifier can be inserted with a load capacity of 20 units.

The power level of the range 1 is higher than in other ranges, in view of the need for maximum possible insensitivity to noise. In each basic circuit 0·5 W is dissipated, and it is possible for one print to contain several basic circuits. The power level is appreciably higher than that of digital computers but is still one order of magnitude below that of light-current relay systems and two below contactor systems. But it is still sufficiently low to enable the space available to be utilized fully without need for additional ventilation.

As already mentioned, the stipulations regarding speed are considerably less exacting for the power engineering range than for the counting range. For ordinary sequential and program control systems it is sufficient to operate at a speed one order of magnitude faster than that of contactor controls. For complex systems controlling mercury-arc rectifiers much higher speeds are required. But even here it is enough to keep one order of magnitude above the repetition frequency of 300 c/s. Having regard for maximum insensitivity to noise, the employment of speed-up capacitors was dispensed with. Hence the maximum transition time from the 1 signal to the 0 signal and vice versa of 60 μs is obtained with a resolving power of 2 kc/s. The repetition frequency is restricted to 1 kc/s in view of the thermal load. These speeds are sufficient for high-speed rectifier controls. In such cases the repetition frequency is generally 50 c/s, at some points 300 c/s.

b. Input units

The task of the input units for electronic open-loop control is to convert all input data into the standardized voltages for the signals 0 and 1. The fundamental duties of these units are: Imparting manual commands, positional or angular commands, commands dependent on time, commands forming part of a program.

TABLE III

The main input data for electronic controls

Basic duty	Type of unit	Typical applications
Manual commands	Key Switch	Switching on, off or over, from control desk or panel
Positional commands	Contactless limit switch Photo-cell	Determining the position of cross-head of machine tools Determining the position of passing rolling stock
Angular commands	Electronic coincidence transmitter	Determining the position of blades of rotary shears
Stored commands	Cross-bar distributor Multikey panel Punched-card reader Punched-tape reader	Programming on machine tools

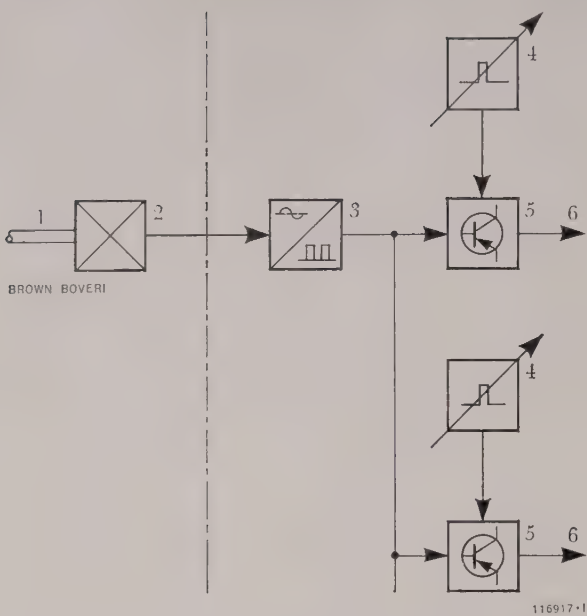


Fig. 3. – Block diagram of an electronic coincidence transmitter

1 = Scanned shaft
2 = Induction system
3 = Generation of measuring pulses from voltage zero
4 = Originator of adjustable setting pulses
5 = Evaluator
6 = Output signal

To perform these fundamental tasks it is possible to call on a wide variety of devices, differing in principle and design. There is no point in restricting the number of units from the very start because there is repeatedly a need of special units for new specific tasks. Consequently those units listed in Table III are to be considered as preferred, but not exclusive means of performing the particular basic function within the scope of the Brown Boveri electronic system. When required, they are also employed for range 2.

It is worth dealing with some points in this Table a little more closely. For imparting commands by hand, keys and switches employed for controlling relays are used. The fact that a voltage referred to a common potential can be used as a signal suitable for infinite ramification does, however, offer one great advantage: It obviates the need for usually expensive and cumbersome switches with several planes which are often inevitable with relay control systems, because the relations in some cases have to be established by connecting contacts in series which are insulated from one another.

To impart commands according to position, either contactless limit switches, e.g. with variable magnetic circuit, may be used or, depending on aptitude, photo-cells for which special steps are taken to avoid the difficulties arising out of surrounding radiation and dirt. For angular commands an electronic coincidence transmitter is available, which emits a signal as soon as the shaft involved reaches a preset angle of rotation. The device thus behaves in the same manner as the well-known mechanical detector. Fig. 3 shows the block diagram of the circuit of the above transmitter. The shaft in question is merely coupled to a simple rotating-field system (2). The setting and evaluating unit is mounted remote in the most convenient position. It contains a device (3) which, from the alternating voltage produced by the rotor of the induction system generates measuring pulses in phase with the voltage zero. For every desired output signal (6) there is a device for generating the adjustable comparison pulses (4) and an evaluator (5), which emits the standardized output signal, or does not, according to whether the shaft (1) is in the angular position determined by the device (4), or not.

Hence the devices (4) and (5) respectively correspond to the cam-operated contacts of a mechanical copying system. The advantage of the electronic system is that it avoids contacts of any kind and, above all, that the setting does not have to be carried out on the actual shaft, but at some remote point. A special arrangement permits certain angular errors to be corrected, such as may result when the induction system has to be re-assembled.

For giving stored commands various methods can be used, such as key panels, cross-bar selectors, punched cards or tape.[2] They may also be used for digital inputs to closed-loop control systems. For conversion into the signals required for the subsequent analogue system the digital-to-analogue signal converters are used.

[2] See pages 706 and 719.

TABLE IV

Basic control units of the power engineering range

Designation	Number of circuits per unit	Task
Signal store	4	Storing a signal at one input and resetting by a signal at another input
Signal blocker 0·5–10 ms	1	Storing a signal for a definite set time
Signal blocker 10–200 ms	1	Storing a signal for a definite set time
Signal blocker 0·2–4 ms	1	Storing a signal for a definite set time
Signal blocker 0·1–70 ms	1	Storing a signal for a definite set time
OR amplifier	3	Relating signals
Signal frequency divider	3	Storing a signal and resetting the store by the next signal at the same input

c. Control units

In these units the standardized signals, emitted by the input units in accordance with external commands, have to be processed into new signals in conformity with the requirements, for the desired operation of the output units. As already explained, these general conditions can be fulfilled with the aid of certain basic operations, for which standardized circuits can be employed.

For execution of logical operations range 1 employs a combination of an OR gate with an inverter, the only difference between which and the NOR gate listed in Table 1 under item 4 is that the output of the OR gate is also accessible. With this arrangement all interlocks required in open-loop control can be effected. Compared with the AND and OR gates its advantage is that its active output can be loaded with five other standard elements in accordance with general specifications. Compared with the NOR gate, its advantage is that the inverse output is also accessible. This property greatly simplifies planning. This combination is referred to as an OR amplifier.

Various other units are available for storage and timing.

The constructional combination of the above basic circuits to produce sub-units on printed circuits is bound to lead to the most economical size of such units. Since each unit is obliged to have a fixed share of the costs, owing to the size of the contact system and the framework, there is not the least point in adopting miniature designs, only suitable for accommodation of a single basic circuit. After exhaustive investigations the best dimensions for the control units of the power engineering range proved to be 192 × 123 mm. An area of this size is not usually fully utilized with only one of the

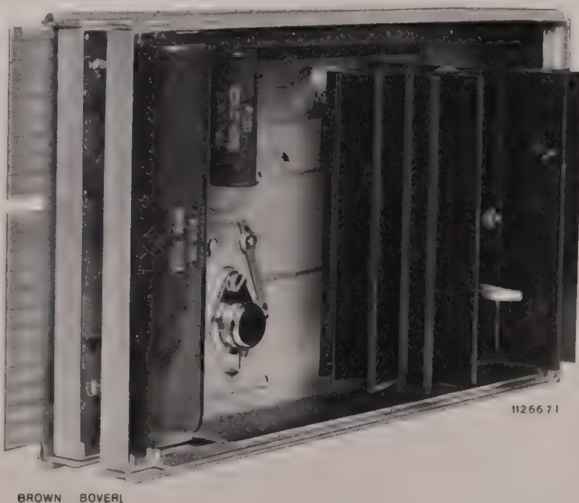


Fig. 4. – Transistorized switching amplifier

Right, the output transistor with cooling element.

basic circuits listed. Therefore it must accommodate several such circuits. These may be, for example, frequently occurring combinations of basic circuits, or a group of several circuits of the same nature, but electrically quite distinct from one another.

In order to combine maximum flexibility with good utilization of the space available, the latter solution was adopted. Similar but independent basic circuits are merely fed at the same voltage, common to all circuits. These basic units are listed in Table IV.

d. Output units

The output units used for open-loop control must take the signal emitted by the control units at their power level, convert it and amplify it so that it can actuate visual alarms or indicator lamps, contactors, couplings, valves, and so on. They may also have to operate switching transductors, thyratrons or transistors. In every case the output units are switching amplifiers (Fig. 4). In the power engineering range of the Brown Boveri electronic system transistor switching amplifiers are available for powers of 2·4 to 145 W, designed for disconnecting inductive loads. Higher powers are handled by transductors or thyratrons.

e. Power supply

Owing to the small size of the individual units, the only economical method of feeding them is on a group basis, in which the d.c. voltage generally required is generated jointly for a whole group of units.

As mentioned already, supply voltages of $\pm$ 24 V are needed for the analogue part and — 24 V and + 6 V for the digital part. Thus only two supply voltages are required for range 1.

For a supply voltage of 24 V there is a series of power packs for currents from 0·35 to 3 A; for 6 V it is enough to have a power pack with a current capacity of 0·1 A, which can feed control units on the 24-V side up to a load of 3 A. All power packs are equipped with a continuous regulating system which keeps the d.c. voltage constant to within about $\pm$ 1%, regardless of mains voltage fluctuations and changes in load. The overall tolerance in the d.c. voltage, including that due to changes in ambient temperature, amounts to $\pm$ 2%. At the same time the regulating system carries out the functions of a filter, ensuring that the output does not contain a peak value of more than 50 mV in the form of harmonics.

The power packs listed are as a rule employed for both open and closed-loop control systems. Under certain conditions, depending on the load capacity, it may be permissible to accept much wider tolerances for the units of the open-loop control section.

Counting Range 2

a. Special requirements

The units of this range are intended for digital measuring and control tasks, for which a relatively high working speed is necessary, in particular program or numerical controls. Installations of this kind, an example of which is the control of a machine tool with punched tape, can easily contain a few thousand transistors and diodes, the price of which plays a decisive part in the total cost of the installation. The price of transistors increases with its electric strength, or the maximum stipulated working frequency. Manufacturers have, however, been producing transistors for some time which are tailor-made for the requirements of these installations. Moreover they are manufactured and tested with great care in order to assure the high standard of reliability which is so necessary. For price and safety reasons their electric strength is relatively low, which leads to a lower supply voltage than that for range 1. The rated value on the power side is — 6 V. For blocking the transistor in the given temperature range an additional positive bias of + 6 V is required. Finally an auxiliary voltage of — 12 V also belongs to the system, enabling the degree to which certain circuits can be utilized to be greatly improved.

The arrangement of the individual circuits is mainly governed by the demand for a sufficiently high working speed. Thus, for instance, speed-up capacitors are used in the bistable circuits, allowing the limiting speed to be appreciably increased. The consequent slight reduction in freedom from noise can be accepted without worrying, as there is little likelihood of powerful noise sources being in the immediate vicinity. Also, extensive use is being made of D signals, derived from the C signals by differentiation with respect to time, the ultimate effect of which is to drive bistable circuits very rapidly with the minimum of energy. For economical reasons, however, it was not possible to attain equal load capacity at the output for all types of circuits. Planning can be carried out quite easily though, with the assistance of load tables. Further information regarding the digital signals may be found on page 669 of this issue.

The working speed attained is sufficiently high for all foreseeable requirements of this field of application. It is best characterized by the fact that the content of a store can be reliably changed with a repetition frequency of 100 kc/s. Thus it is quite feasible, for instance, to traverse at 30 m/min with an accuracy of 0·01 mm. Moreover, in the short time in which the distance of 0·01 mm is covered at that speed, calculations can be performed which are necessary for supervision of the program and for control purposes.

In the applications visualized, the number of analogue units is quite small compared with the digital units. Only the former require stabilized voltage for the sake of accuracy. Digital circuits with transistors are comparatively insensitive in this respect, and there is consequently no point in stabilizing. The circuits of range 2 are therefore dimensioned to tolerate a deviation of $\pm$ 7·5% from the rated value of any source of supply, due to load fluctuation or scatter. The mains voltage is still governed by the tolerances given earlier, provided all power packs are connected to the same supply. However, if the circuits are fed from stabilized sources, the logical outputs may be more heavily loaded.

The power level of individual basic circuits, about 50 mW (with an output impedance of appr. 1 kOhm), is roughly one order of magnitude below that of range 1. Only in this way is it possible to accommodate the large number of transistors in a reasonable space without worrying about disposal of the heat generated.

The choice of the code used for representing the numbers in the control units demands special attention. It must be stipulated that, when inserted by hand, the decimal numbers must be introduced direct without conversion. With punched tape control every digit of a decimal number is already punched on the tape as a row. Also the numbers emitted by the control units must be in decadic form. On the other hand, economic requirements demand that the representation in the control units be in binary form if possible, so that as few stores as possible have to be employed. The conventional solution, and the one adopted in this case, is for coding to be effected in a mixed binary-decimal form. In this every digit of a decimal number is converted into a 4-digit binary code-word, the individual words being placed side-by-side, as in the decimal number. A certain degree of freedom in the choice of the binary code is desirable. Therefore the circuits of the basic units are so arranged that they may be used for the pure binary code, the excess-3 code or the Aiken code, as required. The choice of code is made by external connections.

b. Input units

In addition to the input units described for range 1, the analogue-to-digital converters for digital representation of distances or angular measurements play a very important part. Of the various procedures available, the step-counting method was selected as being most suitable. Every change by a certain small unit (e.g. 0·01 mm) in the dimension being supervised is converted into a pulse, which is counted into a counter. Steps are taken to ensure that the counter reading agrees with the actual measurement at the start of the movement, and that all changes are counted into or out of the counter

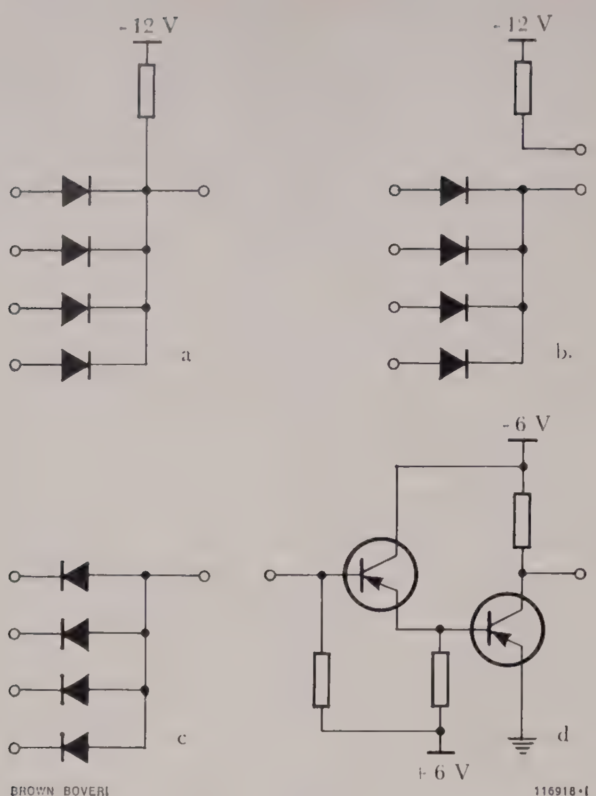


Fig. 5. – Logical block

(All basic circuits indicated are duplicated)

a: AND gates with four inputs
b: AND gates with four inputs, sub-divided
c: OR gates with four inputs
d: Cascade of emitter follower and inverter

in the correct sense. In this way the counter always contains a number corresponding to the actual dimension.

There are various types of pulse converters available, which in principle are designed to supervise angular measurements. Linear movements are therefore first converted into an angular movement, employing the well-known principle of a rack-rod and pinion.

A design assuring maximum robustness with a fairly small resolving power is equipped with the contactless oscillator position indicator [3]. The rotary movement is transferred to a disc with teeth round its periphery, scanned by two such indicators. Every time a tooth passes, each indicator emits a pulse. Since the two indicators are mutually displaced by a quarter of the tooth pitch, the relative phase angle of the pulses emitted can be used to automatically determine the sense of rotation and for counting the pulses with the correct sign. The advantage of this method is the absence of any parts exposed to wear.

For relatively large resolving powers, e.g. to 0·01 mm, a disc with an optical grating is employed which periodically interrupts the passage of light from filament lamps to photo-diodes, causing a pulse to be generated each time. With this method the greater accuracy is obtained at the cost of having to replace the lamps at regular intervals.

For introduction of numbers by hand, ten-position selector switches are used, which produce the four-digit binary code with their four switching planes.

For storing complex numerical input data punched tape is preferred for reasons discussed in a later article (see page 718). The tapes can be produced on normal Flexowriter units.

c. Control units

In range 2 the main task is not so much the formation of logical relations but rather the execution of complicated operations with the digitally coded numerals. The principal parts of these tasks are:

– counting pulses into counters

– holding definite numerical values in stores, and transferring them from one store to another

– continuous or periodical comparison of different numerical values with one another, to establish equality or the sense of a deviation.

To these must be added a number of less important tasks.

In the applications visualized more than half the outlay for circuitry is occupied with the main tasks listed above, as a rule. The process of optimization had therefore to concentrate on the counters, stores, coincidence units, etc., required for the execution of these tasks, the components needed for treatment of a single decimal number being accommodated on a single printed circuit. Although these units are quite

TABLE V

Basic control units of the counting range

Designation	Number of circuits per unit	Suggested tasks
Rotational discriminator	1	Determines the direction of rotation from the phase difference between two sets of incremental impulses
Counter-control unit	1	Controls reversible counters in accordance with result from rotational discriminator, for counting forwards or backwards
Binary tetrade	4/1	a: Quadruple basic circuit of binary stages with controlled dynamic inputs b: Store for reversible counting decade
Logical circuit of counter	1	Logical part of reversible counting decade. Can select pure binary, excess-3 or Aiken code by external attachments
Counting decade	1	Only counting forwards in pure binary, excess-3 or Aiken code
Coincidence circuit	1	Determines coincidence between two binary-coded decimal numbers
Shift register (three-digit)	1	Primarily as neutral selector for filling stores
Comparison circuit	1	Compares two binary-coded decimal numbers for $<$, $=$ or $>$ and gives the result as appropriate output signals
Parity check	1	Checks that information on punched tape is correctly taken up
Coordinate switch	1	Switching information on punched tape to the stores of the associated coordinates
Decade switch	2	Switching over to the associated store within one coordinate
Indication decoder	1	Conversion to decimal from binary code to control an indicator
Indication changeover	1	Switching illuminated decimal indication to desired coordinate
OR amplifier	5	OR gate with 4 inputs, followed by inverter; for relating signals
Logical block	4/2/2	Contains 4 AND gates, 2 OR gates and 2 cascades of emitter follower and inverter; for relating signals
Pulse shaper	3	Restoration of the necessary steepness to the flanks of a C_2 signal
Pulse generator 50 kc/s	1	Generating auxiliary pulses for certain arithmetical operations
C_1-to-C_2 converter	2	Converting C_1 signals into C_2
C_2-to-C_1 converter	4	Converting C_2 signals into C_1
A-to-C_2 converter	4	Converting an A signal exceeding a certain amplitude into a C_2 signal

advanced functional groups, the principle of building up from basic functions was adhered to. For further information see Table V, giving a summary of the main control units.

It is, of course, important to be able to construct the logical circuits required for the control units, as in range 1, in a flexible manner using multiple printed circuits containing several basic circuits each. In addition to an OR amplifier, the range 2 has another printed circuit available, known as a logical block, which is very versatile in its application. It contains four AND gates with four inputs, two OR gates with four inputs, and two cascades, each comprising an emitter follower and an inversion amplifier. The inputs and outputs of all these basic circuits are brought out separately to the plug contacts, two of the AND gates being divisible into two separate parts (see Fig. 5). With such a sub-unit it is possible to produce the logical chain "AND-OR amplifier" which is often required, the subdivision permitting the desired variation in the number of inputs.

d. Output units

The output commands determined by the control units are usually emitted via digital-to-digital converters to the correcting units of range 1. There are also special output units for pure indicating and recording tasks, such as illuminated numerical indicators, or fault indicators with pilot lamps.

(KME)

H. BRÄNDLE
H. LISNER

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THE BROWN BOVERI ELECTRONIC SYSTEM — TELE-OPERATION

621.398:621.38

This article explains the position occupied by tele-operation within the field of information handling. Different methods of solving the problems of tele-operation are discussed and illustrated.

TELE-OPERATION is a clearly outlined special section of the communications field. Strictly speaking, the word itself is not entirely satisfactory, but in view of the lack of a suitable translation for the German term 'Fernwirktechnik', it is adopted for want of a better term. The relationship between the various groups may be expressed diagrammatically as shown at the foot of the page.

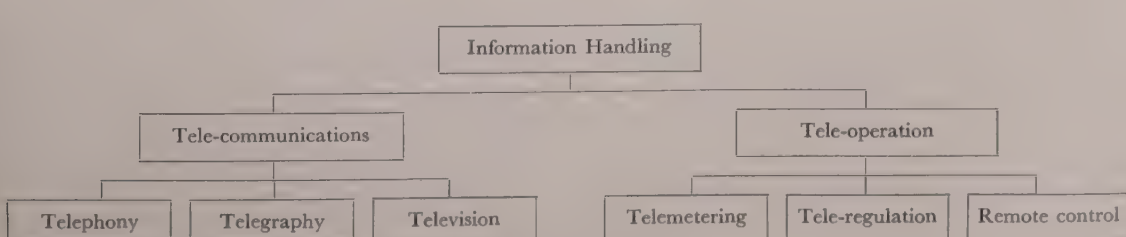
Fundamentally, tele-operation is when an exchange of information takes place between man and machine, or between separate machines or groups of machines, provided there is a spatial separation between the partners. The large and much older field of tele-communications, which is used for the transfer of information from man to man, is not considered in the present article.

The field of application of tele-operation techniques has grown considerably in importance in recent years. Whereas in the past, the course of a particular process could only be controlled from a remote point in isolated cases, there are nowadays countless plants and organizations making use of this facility. In many cases the saving in personnel is not always the sole governing factor behind its adoption, but rather the elimination of human weaknesses.

Wherever man and machine have to work together, man has to be kept informed of the state of the machine at a given instant. If he is standing in the immediate vicinity of the machine, he can make use of all his senses to judge the state of the machine. If, on the other hand, he is some distance away from the machine, he has to rely on a few measurements, transmitted to him with absolute reliability. This is the task of the tele-operation equipment.

The requirements regarding these measurements may, however, differ widely and even be contradictory. On the one hand, they must be transmitted with maximum precision, the speed of transmission being of subordinate importance; on the other hand, it is essential to be advised of the approximate condition of a remote—controlled installation as directly as possible. These requirements become particularly severe when accurate measurements are required as quickly as possible.

In most cases these measurements involve currents, voltages and powers, but often other physical quantities are required, such as temperature, frequency, pressure, volume, level, speed, brightness, colour values, humidity, etc. This list could be extended ad lib. But it is always necessary for



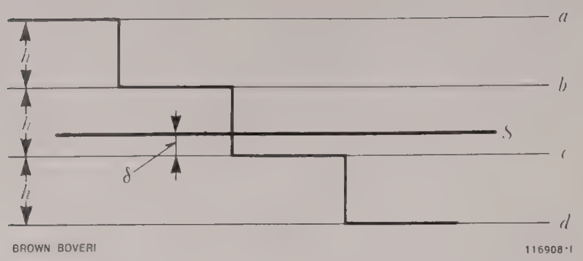


Fig. 1. – Transmission of an analogue value in digital form

S = Desired value (analogue)
a, b, c, d = Values which can be transmitted
c = The digital value actually transmitted
δ = Error of transmission
h = Height of a step

In this case the maximum error amounts to $\delta = h/2$, otherwise the value b would be transmitted.

quantities measured in the remote installation to be converted first into a state suitable for transmission. For instance, with the Brown Boveri frequency-variation system,[1] every quantity which occurs in the form of an angular rotation can be processed direct. Newly developed measurand converters[1] allow currents to be converted very accurately into a variable frequency, without the assistance of any intermediate mechanical element.

Most physical measurands occur in analogue form, and it is therefore preferable for the measurand to be converted into digital form, because this method of representation assures minimum loss of information along the often complicated route between transmitter and receiver, which is subject to all kinds of interference. The reduction in resolving power which has to be taken into account as a result of the conversion from analogue to digital, is counter-balanced by the freedom of the transmission from interference and temperature effects. Moreover, the resolution in the digital system can be increased almost indefinitely, although of course the cost of the installation increases rapidly with greater resolving power.

There is naturally no sense in increasing the outlay unnecessarily; the main point is that the classified accuracy obtained with the transmitter and indicating instruments must not be unduly diminished by the transmission. But since, according to the laws of probability, the errors of the instruments and the errors resulting from resolving are added in quadratic, the resolving power only has to be slightly better than the classified error to disappear quickly with relation to the latter.

$$\text{Resultant error} = \\ = \sqrt{(\text{Class error})^2 + (\text{Resolving error})^2}$$

For 250 steps, referred to the final value, a maximum error of $\pm \frac{1}{2}$ a step can be obtained by graduation of the values, or digitizing. This is no more than 0·2% of the final value. Thus the resultant error for class 1 is 1·03%, for class 0·5 it is 0·56%.

The new digital-cyclic telemetering system[2] developed by Brown Boveri in recent years makes abundant use of the advantages offered by this method.

In addition to continuous quantities, there are others whose variation is of an abrupt nature. For example, a switch is either off or on, a motor is running or at rest, a threshold value is attained or not. In such cases, as far as the information is concerned, either a yes or a no state is involved. Such yes/no signals do not impose any demands on the transmission from the accuracy point of view, but merely demand absolute reliability. In such cases the accuracy can only be with respect to the absolute or relative instant at which an action occurs.

The significance of acknowledgement signals increases with the extent of the remote-controlled installation. Changes in the state of the installation compared with the desired state must be reported reliably, and often recorded too. If faults in complex, intricate installations can be followed rapidly by their consequences, conventional recording devices or systems are no longer capable of discerning between cause and effect. In such cases only a quick-acting indicating system with built-in memory can help; it registers events in chronological order and communicates the information to a more slowly operating data printer, for instance. There are certain cases in which the speed at which the measurand is transmitted is of prime importance, particularly when the telemetering system is incorporated in a widespread control system, e.g. load-frequency control in national or

[1] A. DE QUERVAIN: Cyclic Telemetering, Brown Boveri Rev. 1955, Vol. 42, No. 7/8, p. 262–70.

[2] See page 723.

international electricity networks, remote direction of missiles or vehicles, high-speed distance protection of power lines.

Increasing importance is being attached to communication between widely separated machine installations. Here man does not have to intervene; the exchange of information takes place automatically, e.g. distance protection. In such cases the main stress is on absolute dependability and a comprehensive indicator system, which signals a possible fault or gives an alarm automatically. Often, the tele-operation equipment is duplicated in such cases to attain maximum reliability. If remote-controlled installations have to operate in conjunction with computers and evaluators, it is usually necessary for a tremendous amount of information to be transmitted from the plant to the evaluation point. In this case the main problem is the bandwidth. The new digital-cyclic telemetering system with staggered transmission of individual items of information may be employed with advantage in such instances.

Having now received the information required with the aid of a dependable system, and being aware of the state in which the remote machine and equipment is at the moment, only one prerequisite for correct intervention is fulfilled. An absolutely reliable medium is now needed to enable man to execute the action which he decides is necessary from the information received. This medium is the remote-control equipment.[3]

Here safety is the predominant factor. It is therefore not sufficient for a modern remote-control system merely to transmit a command, it must also signal back that the command has in fact been executed. In contrast to telemetering, the majority of the information involved in remote control is discontinuous. Most of the commands are of the on/off kind. Commands of a more/less nature are either executed by a series of on/off commands, the result obtained being telemetered or communicated by means of a telemetering channel whose input units are on the control side and whose ouput units are equipped with an automatic mechanism, which brings the machine to the required position.

In remote control the speed is important, in that for a large remote-controlled installation with a number of substations, the process of scanning to determine the state of the station must not last unduly long. With the newly developed system of pulse-code remote control, the transmission time is so short that reasonable scanning times are obtained, even when there are hundreds of commands. In spite of the fact that a minimum of time is available for transmission, execution and acknowledgement of an order, comprehensive counter-measures have to be taken to ensure that false operations are impossible. Intricate systems are responsible for the execution of the commands, even in the face of extremely severe momentary disturbances. The almost instantaneous operation of the remote-control system allows synchronizing commands to be given and executed, for instance.

The measurands which have to be transmitted are available at the input end all the time. If they were transmitted at the same time, i.e. in parallel, this would involve an unreasonably large bandwidth, because it would be necessary to provide, say, 120 c/s for every measurand. By staggering, i.e. transmitting in series, and indicating the measurands in parallel, it is possible to save a considerable amount of bandwidth. A primary condition, though, is that the change in measurand between one transmission and the next must not be too large, or information may be lost. This is where the advantages of coding become most evident, because the repetition frequency can be increased without the accuracy suffering, provided the nature or number of measurands make this necessary.

As may be gathered from the foregoing remarks, the field of tele-operations covers three main sections: telemetering, tele-regulation and remote control. The equipment used in all three of these sections includes input units, transmission equipment and output units.

In order to comply with the wide variety of practical requirements, the following new units were developed as part of the tele-operation range of the Brown Boveri electronic system:

(a) Input and output units:
- digital cyclic telemetering equipment (see page 723)
- pulse-code remote-control equipment (see page 732)

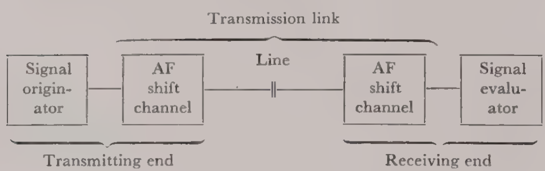
[3] See page 732.

(b) Audio frequency shift channels as an integral part of conventional transmission links:

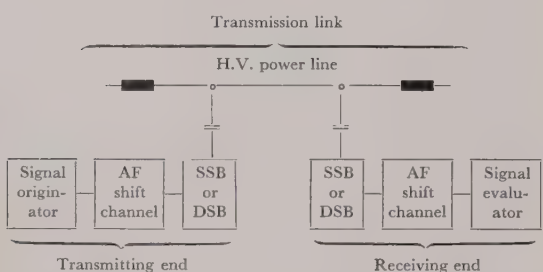
- pulse channel
- carrier transfer channel for distance protection
- transformer protection channel

Depending on the conditions obtaining, a number of different methods can be selected for the actual transmission of the information.

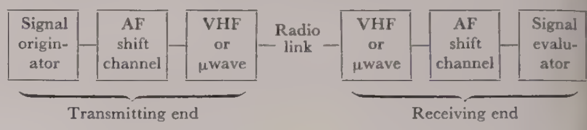
1. *Transmission at audio frequency over wire*



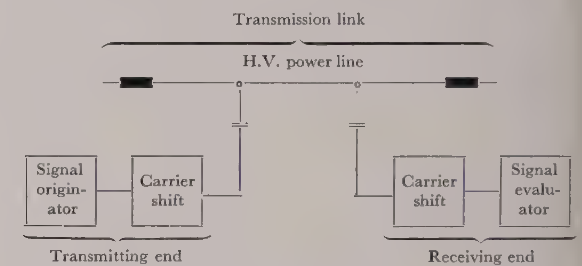
2. *Modulation of a single or double-sideband unit to transmit the carrier signal over a power line*



3. *Modulation of a v.h.f.-or microwave unit, the information being transmitted by radio*



When very short transmission times are stipulated it is possible to employ carrier frequency shift units. In this case the carrier signal is not frequency-modulated with different discrete audio frequencies, but is itself displaced in its frequency.



Both audio and carrier frequency shift channels can be supplied with a two or three-position shift, according to the particular application, the bandwidth required depending on the frequency and the desired speed of transmission. For both a.f. and carrier shift an interval of 120 c/s was selected.

(KME) M. SCHÖNSLEBEN

BROWN BOVERI ELECTRONIC SYSTEM—COMPUTER TECHNIQUES

681.14–838

The variable quantities which have to be processed by digital computers used for industrial applications arrive continuously at the input. The computer processes them discontinuously, but the clock frequency is made very high so that, when measuring frequency for instance, a high accuracy is obtained, while with digital control, stability is assured. Moreover difficult optimizing tasks can also be performed.

THE MAIN tasks confronting digital computer techniques for industrial applications are: the measurement of frequency, digital control and optimization. In contrast to computers used for applied mathematics, the data to be processed are not introduced at one time, but continuously present at the input in the form of a momentary value. By means of a master clock the momentary values are successively transferred to the computing system proper via an analogue-to-digital converter (sampled data system). The sum of the transfer and computing times in digital controllers must, for stability reasons, be less than the smallest system time constant. Having regard to this fact, the computer range of the Brown Boveri electronic system has a clock frequency of 1 Mc/s.

The following remarks may be made regarding the tasks referred to above.

Measurement of Frequency

For the digital measurement of frequency two different methods can be used.

a. Counting the cycles of the actual-value frequency, or a multiple of it, in a fixed period.

b. Counting the cycles of a standard frequency during one or more cycles of the frequency being measured.

For both methods it is essential to have a high clock frequency for the basic circuits if the actual value has to be determined with great accuracy in rapid succession. The clock frequency of 1 Mc/s allows, for instance, a frequency to be measured to an accuracy of 0·01% in 0·01 s.

Computing by Counting

In addition to the procedures usual with digital computers, such as *parallel and series operation*, another may also be used, i.e. *counting*.

With *parallel operation* all digits of two numbers (operands), with which one of the basic arithmetical operations has to be performed, are processed simultaneously. With *series operation* the digits of the operands are processed simultaneously according to their order but one place after another, being introduced into one computer cell and the resultant digits transferred at the same rate to the result store. With the *counting* method numbers of pulses corresponding to the numerical values of the operands are successively counted into the arithmetical unit.

Assuming the basic circuits all have the same working frequency, the time taken in calculation by parallel operation is shortest, while by the counting method it is longest. The outlay for circuitry is in exactly the reverse relationship, i.e. largest for parallel operation and smallest for the counting method.

The price of a unit is proportional to the extent of the circuitry; therefore it is preferable to perform calculations by counting in those cases in which the nature of the operations, the stipulated accuracy of the result, the time available for evaluation, and the working frequency of the basic circuits permit.

The counting method is mainly suitable for addition, subtraction, integration and differentiation, i.e. for those operations necessary in digital controllers. Here the result is identical with the correction, which has to be converted into an analogue quantity, such as current or voltage, for further processing in the correcting elements. Conversion from digital to analogue form can only be performed, even at the best, with an accuracy of 0·1%, so that three decimal places in the control unit are sufficient. With the units of the computer range, for instance, with a clock frequency of 1 Mc/s, it is possible to add or subtract two numbers between 0 and 1000 in at the most 0·002 s.

The article on the digital system controller (see page 741) describes the methods of forming the deviation and processing it employing the computer techniques of the Brown Boveri electronic system.

Optimization of Processes

When the course of a process allows a number of alternative solutions to be adopted, it is often necessary to undertake extremely complex calculations before that possibility can be found which provides the most economical or optimum technical result. The introduction and processing of the input data, which is often very extensive, requires a certain amount of time on the one hand, while, on the other, only a limited time is usually available for the result to exert an effect on the course of the process. To solve such problems with digital optimizing devices it is also essential for the basic circuits to have a high clock frequency.

The duties of the optimizing system can be illustrated by an example. In the network of an electricity undertaking with several hydro-electric stations the power required by consumers has to be produced at the most favourable price, allowing for the hydraulic conditions and line losses. *Fixed input data* are the cost of generation per kWh, the efficiencies of the various stations between no-load and full load, and the line data. *Variable input data* are the flow of power in the network and the water levels. From these variables the optimizing equipment has to emit correction commands to the individual turbines, to ensure that there is no loss of water and to attain a minimum price per kWh.

From the consideration that equipment of high quality for data processing is housed in special enclosures and in any case is installed in rooms which are air-conditioned for the personnel, the requirements as regards robustness and temperature range can be somewhat eased, to the benefit of a higher working frequency.

(KME) H. BLOCH

AUTOMATIC SCREWDOWN CONTROL IN ROLLING MILLS WITH PUNCHED-CARD PROGRAMMING

621.771.2-52

A major step towards automatic control of rolling mills is the automatic adjustment of the positions of the rolls—or screwdown as it is called. The principle and design of the system of positional control in conjunction with programming are explained in the present article. Punched cards are ideal for storing the program. Their arrangement as information carriers is described with reference to a program card for screwdown control in a rolling mill.

FOR THE automatic control of reversing rolling mills it is essential for the width of the gap between the rolls to be automatically adjusted in accordance with a preset program. From the technical aspect this is a positional control with programming in digital form. The problem is precisely the same as positioning the cutting steel on machine tools. Whereas in the latter case three coordinates generally have to be programmed for a single point in space, screwdown control only involves unidimensional programming. The various gaps which have to be successively adjusted are represented directly by decadic numerals, referred to the predetermined zero position of the upper roll. The graduation for programming is generally in stages of 0·1% of the total distance; it can, however, be reduced to suit requirements, almost without restriction.

Design and Principle of Program Control

The factor which decides what kind of equipment shall be employed for positional control is the kind of measuring system adopted for the value representing the momentary position. The basic principle is illustrated by Fig. 1. By nature the system is analogue. Its mode of operation can be explained by studying a copying system, as example. The straight-line motion of the detector is converted by a rack and pinion into a rotary movement of the rotor. The latter has a single-phase winding, applied to which is an alternating voltage. The stator, on the other hand, has three windings mutually displaced by 120° and connected in star. The primary rotor winding induces in these stator windings three voltages, denoted by U_{xz}, U_{yx} and U_{zy}, respectively. The magnitude of these voltages depends on the geometrical

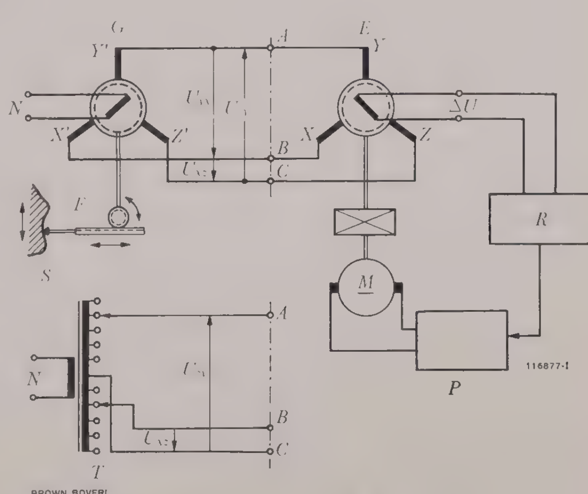


Fig. 1. – Schematic circuit diagram of the synchros with analogue or digital setting of the desired value for controlling distances

N = Mains
G = Transmitter
E = Receiver
F = Detector
S = Template
R = Controller
P = Power amplifier
M = Motor
ΔU = Error voltage
T = Transformer for positional desired value
X, Y, Z = Stator windings of receiver
X', Y', Z' = Stator windings of transmitter

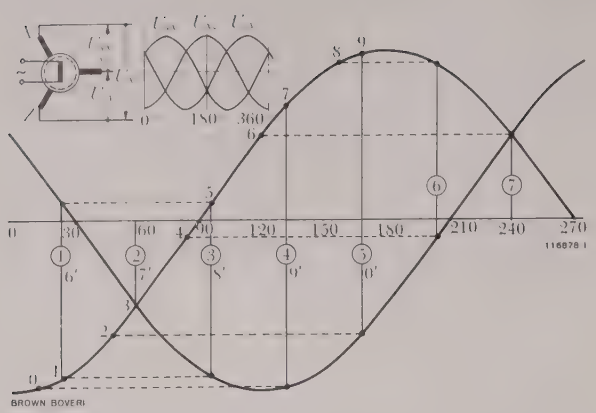


Fig. 2. – Voltage values for a coincidence transmitter

For a decimal position the digits 0 to 9 are digitally programmed.

position, i.e. the angular rotation of the rotor, and their sum is always zero.

The ends of the transmitter windings are connected to the stator windings of a receiver. These induce a voltage in the receiver rotor, known as the error voltage. Its magnitude likewise depends on the angular rotation of the receiver rotor, and it is zero when the windings of transmitter and receiver are mutually displaced by 90°, as indicated in Fig. 1.

When the error voltage becomes zero, the alternating voltage performs a phase shift of 180°. When rectified in the proper phase relationship the error voltage gives a direct indication of the deviation of the momentary position from the desired position. The error voltage is applied to the input of a controller. This drives a push-pull power amplifier which feeds the d.c. motor. The motor, acting through gearing, drives the cross-head of the machine, not shown in Fig. 1. Coupled to the same gear is the rotor of the receiver, so that the cross-head and rotor are always adjusted in the direction of zero error voltage.

This analogue transmitter system can easily be replaced by a digital system. The leads to the stator windings are then disconnected at the points *A*, *B* and *C* and taken to the corresponding terminals *A*, *B* and *C* of a single-phase transformer. As already mentioned, the sum of the three voltages is always zero. Hence, to obtain an unambiguous definition of a position or the relevant angular position of the receiver rotor, it is sufficient to specify two voltages for the stator windings; these are denoted by U_{xz} and U_{zy}. These two voltages are obtained from the tappings of a single-phase transformer. The great advantage of this is that, in the event of fluctuation of the mains voltage, the two secondary voltages both vary exactly in proportion. The accuracy of the ratio of the two voltages cannot therefore be affected.

Thus to preset the digital desired value of the position of a decimal with the digits 0 to 9 requires twenty tappings; with skilful arrangement of the zero position this number can be reduced to ten, as indicated in Fig. 1.

Conditions are illustrated somewhat more clearly by Fig. 2. For a full revolution (360°) of the transmitter rotor the amplitudes of the alternating voltages in the three stator windings vary according to a sine function. To set the desired value, the two voltages U_{xz} and U_{zy}, for instance, are used. Their envelopes for an angular rotation between 0 and 270° are the two sine curves drawn to a larger scale. All voltages values needed for programming the digits 0 to 9 of a decimal are denoted by the points 0 to 9 on the curve of U_{zy}. These ten voltages can be tapped off the transformer.

This sketch illustrates how easy it is to program the digits 0 to 9 by the application of two voltages. The digit 3, for example, is represented by tapping 5 off voltage U_{zy}, and by voltage U_{xz} tapped off point 1 of the same transformer.

The remaining digits can be programmed in like manner. It must, however, be borne in mind that the voltage values for the digits 6 to 0 are exactly the same as those for 1 to 5, on account of the symmetry of the arrangement. They are merely applied to different stator windings. This may be seen from the following comparative table:

Digit	1	2	3	4	5	6	7	8	9	0
Tapping for U_{zy}	1	3	5	7	9	8	6	4	2	0
Tapping for U_{xz}	5	3	1	0	2	4	6	8	9	7

The tappings corresponding to the digits 0 to 9 are connected in pairs and in the simplest case each digit is allocated a relay with two normally-open contacts. However, transistor circuits have also been devised, by means of which the alternating voltages can be switched from the transformer tappings to the stator windings of the receiver without any contacts but still with the necessary

precision. This facility is particularly important in situations where extremely high reliability in continuous operation with minimum attention is stipulated. This is the case in rolling mills and it therefore follows that the system described is valuable for the automatic screwdown control.

When used in conjunction with digital programming, the above synchro systems offer two important advantages for all positioning tasks: Firstly, the momentary positional value is determined quite definitely, regardless of what preceded it either electrically or mechanically. The sole prerequisite is that the moving machine part must be rigidly coupled to the rotor of the receiver. The movement of the upper roll spindle is thus transmitted without any play to the rotors of the receivers through a precision gear.

Secondly, mention must be made of the high resolving capacity. Transmitters can already be obtained with an angular accuracy of 30″. This implies that, taking full advantage of their electrical accuracy, four full decades can be covered by a single transmitter with decimal setting of the desired width of the gap, namely:

10 steps each of 36°	in the first decimal place
10 steps each of 3·6°	in the second decimal place
10 steps each of 21·6′	in the third decimal place
10 steps each of 2·16′	in the fourth decimal place

This means that additional transmitters are only required for the measuring system when more than four decimal places have to be programmed.

A practical arrangement of two synchro transmitters combined with gearing and a mechanical dial for indicating the momentary positional value is shown in Fig. 3. This is a device used with punched-card programming for screwdown control in a rolling mill. For various reasons the high accuracy of a single synchro transmitter was only partly utilized, thereby necessitating two units (coarse and fine). These can be seen at the bottom of the gearbox unit on the right in the picture. The size of the solid gearbox is determined by the built-in dial indicating the width of the gap and must not lead to false conclusions being drawn regarding the necessary torque, or the like.

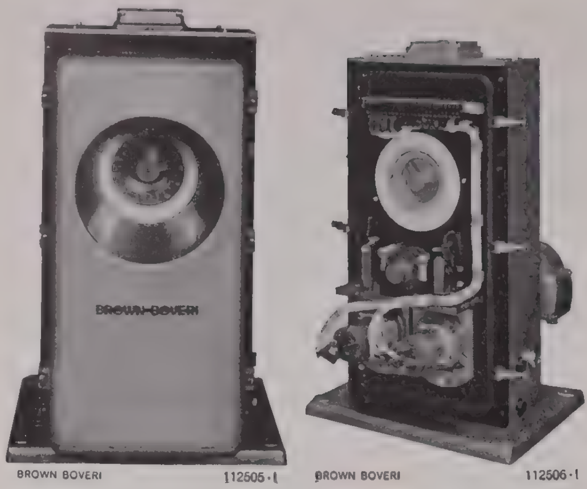


Fig. 3. – Actual-value gearing with two synchro transmitters and mechanical dial indicating the gap between rolls

Right (without enclosure) shows two synchro transmitters for coarse and fine control, at the bottom of the gearbox. The total displacement of the roll is 250 mm. This can be adjusted in steps of 0·1 mm.

Program Store

The choice of a suitable means of storing the program is governed by the nature and scope of the program. If the program control contains only a few functions, and if changes in the program are relatively infrequent, e.g. not more than three to five times per eight-hour shift, cross-bar selectors or combinations of decade switches can be used for storage, setting being performed by hand by the machinist. Such simple methods of storage, however, demand the provision of a large amount of equipment. Fig. 4 shows the program storage system for the screwdown control, on the control pulpit of a rolling mill. It is capable of storing three different programs simultaneously, each with fifteen passes. Three decade switches allow the gap to be adjusted for each pass to an accuracy of 0·1%. Compared with many other kinds of store, this kind has the advantage of allowing the machinist to intervene in the set program at any time. This feature is particularly important when new programs have to be laid down after a trial, because it is not always possible to determine the effect of all parameters on the final shape of the rolling stock in advance.

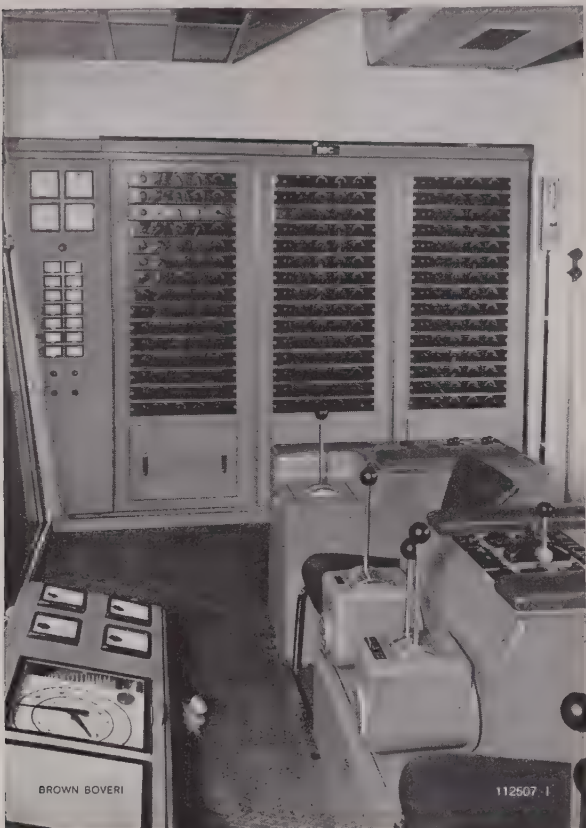


Fig. 4. – Control pulpit of a blooming mill

In the background are the program storage units for screwdown control for three programs each with fifteen passes.

Fig. 5. – Punched-card reader for automatic program control

The moving card holder contains a punched card with the program for screwdown control.

For programs with a limited information content and frequent changes of program, the most suitable storage medium is the punched card [1].[1] This, for instance, is the case with reversing mills; in universal mills the rolling program can change from one billet to another, so that a separate punched card has to be prepared for each billet.

A general advantage of punched cards as a means of storing which is worth mentioning is the relatively short access time; a particular card can be selected from a large stock of cards in quite a short time. For the program control itself a reader is required (see Fig. 5); this simple machine is a development from a standard batch-produced punched-card machine such as is used for administrative problems, with a few additions and modifications. It successively scans one column of the card after another. The information content is conveyed to a command store in the form of switching pulses, the task of which is to store the entire information content up to the length of a "word" until the corresponding step in the program has been executed and the next word can be read.

The term "word" has the same significance here as in computers [2]. It is a group of different numbers of separate items of information which always belong together. The word may be of any length; for a certain installation though it is usually constant, so that items of information which are not required have still to be programmed, e.g. as zero.

The upper half of Fig. 6 shows a normal punched card of the kind commonly used for administrative purposes. It is punched with the IBM code [3], a feature of which is that all digits appear direct in the "1 from 10 code". The 26 letters of the alphabet are coded in the "2 from 12 code" and are easily learnt. This code has a high redundancy, but it does offer the marked advantage of permitting all numerical readings to be read off easily by unskilled persons. Numerals can also be transferred to the punched card as binary digits. When full advantage is taken of the twelve possible spaces in which a hole can be punched in one column, it is possible to accommodate the numbers from 0 to 4096 in a single column, because the binary digit $2^{12} = 4096$. The

[1] The figures in brackets refer to the bibliography on p. 707.

redundancy of the code is then least but the numbers cannot always be read.

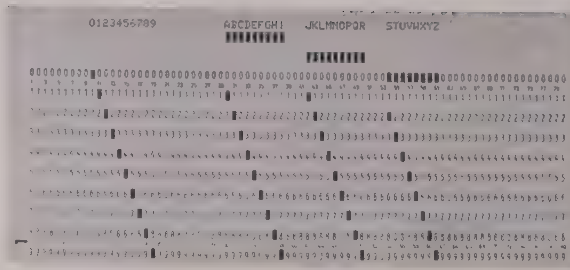
At the bottom of Fig. 6 a program card for screw-down control in a rolling mill is reproduced. On it eleven passes are programmed. Here a word comprises five columns. In the first four columns is the size of the gap; 61·5 mm in the fourth pass, for instance. In the fifth column the control of the side-guards is programmed with the digits 1 or 2.

In the first column of the card there is a hole punched in space 11. This is used to check the position of the card in the reader and is scanned at the beginning of the program. At the end of the program there is a hole in the 5th column in space 12. This hole controls the automatic return of the card holder to the starting position ready for the next first pass.

The card illustrated can be used to program a total of 14 passes. The remaining columns can be used for additional numbers as combinations of holes, e.g. for reference numbers.

As automation progresses, punched-card systems are being increasingly adopted for factory administration, and an existing punched-card machine can also be used to produce the programming cards. It may ultimately be possible for the cards to be produced automatically when customers' orders are processed with a program-controlled computer, once the machine has determined the most favourable program in a particular case.

In automatically controlled rolling mills the preparation of the punched cards comes under the heading of planning. The composition of the program demands a wealth of technological experience, which can only be possessed by appropriately trained personnel [4]. This will apply to an even greater extent in the future when other tasks besides screw-down control have to be performed by punched-card systems. All problems connected with the most suitable arrangement of the cards, such as the length



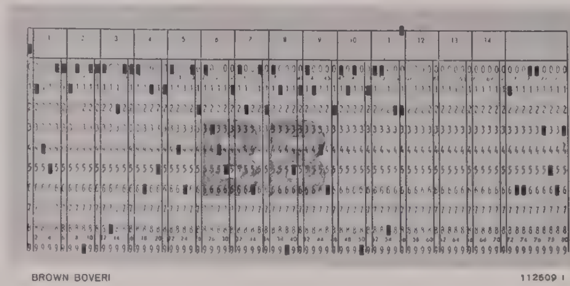


Fig. 6. – Punched cards for program control

The upper card shows the code for numerals and letters. The lower is for screwdown control of a rolling program with eleven passes.

of word, coding, readability, etc., will have to be solved for each separate case, according to the task imposed. They should, however, always be considered from the aspect of utilizing well-tried machines from the administrative sphere to prepare and read the punched cards used for control purposes.

(KME) H. CORDES

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[3] H. L. THOLSTRUP: Perforated Storage Media. Elect. Mfg 1958, No. 12, p. 53–61.

[4] H. CORDES: Lochkarten-Steuerungen für Walzwerke. Stahl u. Eisen 1959, Vol. 79, No. 17, p. 1218–20.

THE USE OF THE BROWN BOVERI ELECTRONIC SYSTEM FOR THE CONTACTLESS CONTROL OF SLOTTING AND PLANING MACHINES WITH NUMERICAL PROGRAMMING OF THE FEED

621.912-52

The use of modern high-power reversing drives for slotting and planing machines introduces particular requirements with regard to working speed, reversing precision and reliability. Brown Boveri have recently designed a new drive with electronic control; the necessary switching processes are carried out by means of elements working without contacts and thus not liable to wear and tear.

This present article, after some basic explanations, deals with the preparation of the desired values and reference input voltages needed for control from analogue comparison values and relevant digital commands and information regarding distances. This contactless technique, based on the Brown Boveri electronic system, is explained by a functional description.[1]

Conditions

THE basic conditions of the specification determining the desired properties of such drives are as follows:

1. Contactless control of the cycle must be provided for the working stroke and feed, repeating itself up to 6000 times an hour. Control elements subject to wear and tear are thus avoided, giving the greatest possible reliability.
2. The continuously variable cutting speed must be kept constant to within a few percent, independently for the forward and return motions.
3. Acceleration and braking times must be as short as possible.
4. The reversal point must remain the same over the whole control range. For this the braking distance proper has to be a minimum.
5. It must be possible to insert special movement programs for particular properties, e.g. storing a stop command until a predetermined end position is reached, synchronizing the feed motion with the working stroke or the latter with other machine functions, interlocking switches, etc.
6. Manual control and simple foolproof operation must be possible.

Control of Constant Reversal Point

Of these conditions the most important is keeping the reversal point constant over the whole control range. This calls for particular measures, the special problems of which must first be solved.

The basic requirement for fulfilling this condition is that the point at which the reversing signal is given should always be reached at about the same approach speed. For this reason a braking process, dependent on the speed, must first be initiated. The effect of the rapid acceleration in the opposite direction which takes place at the moment of reversal is that the small amount of scatter in the approach speed only becomes apparent as a very small difference in distance. On this basis it is possible to build up a reversal system which satisfies practical requirements with sufficient accuracy and at the same time keeps the cost of the apparatus within reasonable limits.

Fig. 1 shows the relationship of the desired and actual values for various speeds during the reversal process in the form of a time-speed diagram. The reversing procedure is as follows: at a distance A before the actual reversal point a saw-tooth reference voltage becomes due. This has no effect

[1] F. GLANTSCHNIG: Contactless Electronic Control of a Rapid-Reversing Drive. Brown Boveri Rev. 1960, Vol. 47, No. 3, p. 131-6.

as long as it is larger than the desired value already set, but as soon as the reference voltage becomes equal to or less than this desired value, the desired value will follow the reference voltage and the machine will be braked. The motor speed, however, only follows this change in desired value after a definite time which can be referred to as the dead time t_T of the control cycle. During this time, which remains more or less constant over the whole control range, a distance approximately proportional to the set speed is completed. With fast reversing drives, for which the braking time t_B and this dead time are of the same order, it is necessary to allow for this influence.

A is kept constant independent of the speed setting and is determined by the dead time and the shortest possible braking time $t_{B_{max}}$ at maximum speed. $t_{B_{max}}$ is calculated from the drive rating for a definite machine, i.e. on the available or necessary braking torque and on the largest mass which must be decelerated, having regard to the losses caused. For all other more favourable cases, i.e. smaller speeds and smaller masses, the drive will then always be capable of following the desired value.

In order that the approach speed to the reversal point may be attained with constant lead distance *A*, the speed-time integral must be constant. Referring to Fig. 1, this means that the area enclosed between the actual-value curves and the coordinate axes must always be the same.

Without going into the mathematics in detail, the necessary slope of the reference input voltage *(S)* can be written as

$$S = \frac{v_{max} \cdot p\left(1 - \frac{p}{2}\right)}{t_{B_{max}} \cdot \left[\frac{1}{2} + (1-p) \cdot \frac{t_r}{t_{B_{max}}}\right]}$$

in which

v_{max} = maximum speed

$p = \dfrac{v}{v_{max}}$ = ratio of set speed to maximum speed = angle of rotation of the desired-value potentiometer.

This relationship is valid for zero approach speed. As the approach speed is very small, this assumption has no appreciable effect.

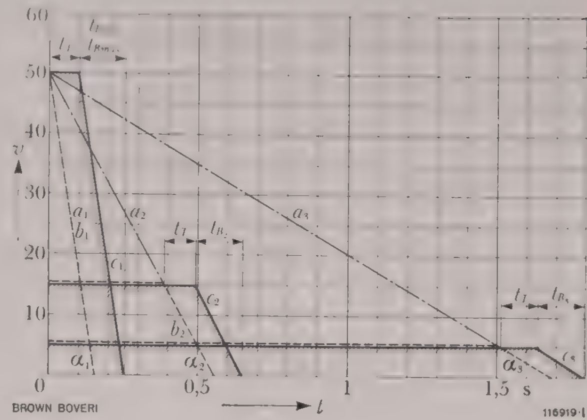

Fig. 1. – Time characteristics of reference input voltage, desired value and actual value for different speeds after the beginning of the reversal process

a = Reference input voltage
b = Desired values
c = Actual values
t_T = Time-lag of the control circuit
t_B = Braking time
S = Slope of the reference input voltage (tan α)
v = Speed, proportional to reference input voltage

The reference input voltage is produced by means of a Miller integrator, in which the slope of the corresponding linear saw-tooth voltage is proportional to the controlling current. In analogy, then, this is evolved as the stated relationship from the maximum desired voltage value and a combination of resistances varying with p.

The Reference Input and Program Unit

With the basic elements of the Brown Boveri electronic system the circuitry of the reference input and program unit was designed to comply with the above and other specified conditions. The unit consists of an analogue part and a digital control part and is, in point of fact, the true control and monitoring centre of the set.

a. The Analogue Part

The object of the analogue part is to prepare the desired values and reference input voltages required for the control and reversal of rotation on receipt of commands from the control part. The two functional groups (1_1 and 1_2 in Fig. 2), designated

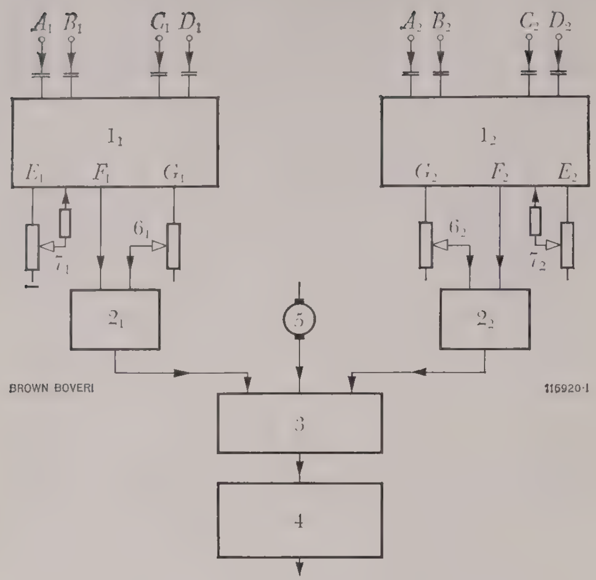

Fig. 2. – Block diagram of the analogue part of the reference input and program unit

The function units 1_1 and 1_2 give the independent desired value and reversal control voltages on actuation by signals from the digital control part.

1 = Desired value generator with integrator
2 = Smaller-than circuit
3 = Mixing amplifier
4 = Control amplifier
5 = Tacho-generator
6 = Desired value setting elements
7 = Function generator for the integrator

"desired-value generator with integrator", act at the same time as digital-analogue converters.

Fig. 3 shows the internal arrangement of the basic elements of these functional groups. The store 1 switches a voltage to the correcting element for the desired voltage (6_1 or 6_2 in Fig. 2). In addition it requires a D signal (differentiated C signal) at input C. A corresponding signal at input D switches the desired-value voltage off again. The store 2 controls the integrator 4 via the AND gate 3. A D signal at input A allows the integrator to discharge, assuming the desired value store 1 is in state 1, thereby fulfilling the AND condition at the AND gate 3. At the same time as the desired-value store is switched off the integrator is reset by a D signal at input B. The Miller integrator, an amplifier with capacitive negative feedback, receives its control current from the connection E and delivers the requisite saw-tooth voltage at output F.

The complete analogue part is shown in Fig. 2 in the form of a single-pole block diagram. Since it is necessary to be able to set the forward and return motions independently, a reference-value generator with integrator and relevant "smaller-than" circuit is included for each (2_1 and 2_2, respectively). Either one or the other reference-value generator is switched on by the corresponding signals from the control part (inputs A_1–D_2). Interlocks ensure that both cannot possibly be switched on at the same time. The desired voltage value, reduced by the correction unit, with the integrator voltage, is fed to a "smaller-than" circuit. The function generator 7, coupled with the reference potentiometer 6, delivers the integrator control current which determines the slope of the saw-tooth voltage. The smaller-than circuit always passes on the smaller of the two input voltages as output voltage, thus providing the curve of the desired value, as shown in Fig. 1. The mixer 3 forms the input voltage for the control amplifier 4 from the desired and actual values.

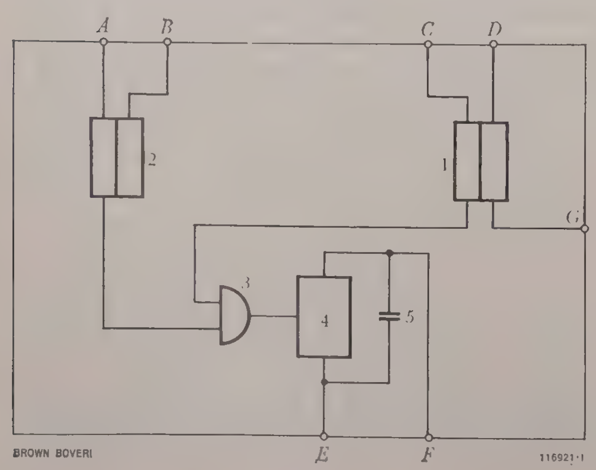

Fig. 3. – Simplified functional circuit diagram of the desired-value generator with integrator

Different basic elements of the Brown Boveri electronic system are here designed as one functional group

1 = Desired-value store
2 = Input store for the integrator
3 = AND gate
4 = Amplifier with capacitive negative feedback (Miller integrator)
5 = Feedback capacitor, determining time

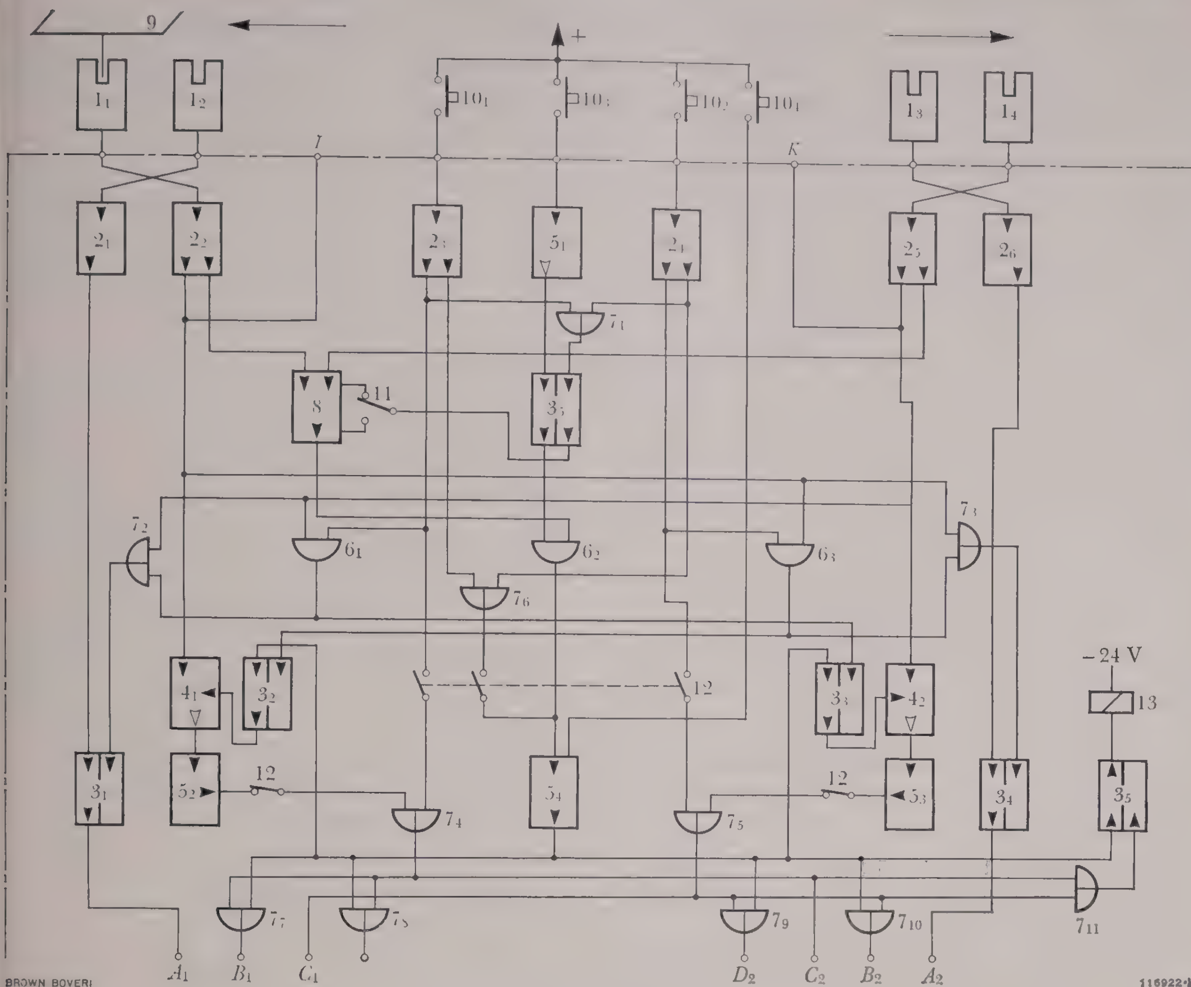

Fig. 4. – Block diagram of the digital control part

In the diagram the circuit is made up of basic elements. In the actual equipment several basic units are combined to form a functional group.

1 = Oscillator position indicator
2 = Pulse shaper
3 = Store
4 = Delay device
5 = One-shot multivibrator
6 = AND gate
7 = OR gate
8 = Transposing network
9 = Element indicating working stroke
10 = Push button for manual commands
11 = Selector switch for setting "stop"
12 = Adjusting switch
13 = Signalling relay for operational state

b. The Digital Control Part

The orders given by hand and the signals coming from the machine have to be converted, i.e. partly amplified and combined logically, corresponding to their set task, so that the necessary signals for the control of the analogue part are available at the output. This is the task of the digital control part.

Those basic elements which are necessary for the direct control of the working motion of such a drive are depicted in Fig. 4 in the form of a block or function diagram. The monitoring devices, as well as further combinations with other motions of the machine, are omitted here for the sake of clarity.

The control part fulfils the following functions:

1. Switching over the desired value from forward to return motion.
2. Initiating the reference input voltage.

3. Storing a stop command until a chosen reversal point is reached.
4. Immediate stop as a separate command.
5. Switch-closure interlock, so that running is only possible from an end reversal point and then only in the right direction.
6. Signalling the "stop" state externally.
7. Setting-up, in the sense that, when the buttons for forwards or reverse are pressed, an ON command in the corresponding direction is given and on release a STOP order. The lead signal and reverse signal of the machine are thus rendered ineffective.

The working motion is checked without contacts by the oscillator position indicators, as described in the March 1960 issue of the Brown Boveri Review. They give a signal which is converted into the standardized C signals by a subsequent pulse generator. The manual orders are given with push-buttons and switches.

This application is a comprehensive, though by no means simple, example of the use of the Brown Boveri electronic system. In order to show how the stipulated conditions are met here, as opposed to former relay circuits, the sequence of events in a working cycle followed by a stop command will be described in detail.

Assuming the table or ram is at rest at the left-hand reversal point, as is shown in Fig. 4; the oscillator position indicator 1_1 is thus in the signal position. The signal 1 is emitted at the left-hand output of the pulse shaper 2_2 and the corresponding inverted signal 2 at the right-hand output. 4_1 is a D-signal retarder which, after a definite time-lag, conveys the normal incoming signal from 2_2 to the output amplifier 5_2. However, should a C signal 1 be received at the control input to 4_1 from the store 3_2, the signal from 2_2 will be delayed until 3_2 changes to state 0.

If now the order for motion towards the right is given by pressing the button 10, the pulse shaper 2_4 emits the signal 1 from the left and the inverted signal from the right-hand output so long as the button is pressed. Thus the AND condition is fulfilled by AND gate 6_3. The signal goes through and changes the store 3_2 to the state 0. The signal which has meanwhile been delayed in 4_1 is now released and, after being amplified by 5_2 and passing through the OR gates 7_4, 7_7 and 7_8, arrives at the control inputs to the analogue part B_1, D_1 and B_2 (see previous section). The necessary desired value for motion to the right is thus brought into action. At the same time the signal from 5_2 arrives at the store 3_5 via the OR gates 7_4 and 7_{11}. This switches a relay which gives the external signal for the ON state of the drive for the other parts of the machine control system. The signal from the AND gate 6_3 brings the store 3_4 to the 0 state via the OR gate 7_3. When the working motion, moving to the right, reaches the position indicator 1_3, the store 3_4 is switched to 1 via the pulse shaper 2_6 and passes its output signal to the analogue entrance D_2. The integrator cuts in and the drive is braked. 1_4 signals that the right-hand reversal point has been reached and the pulse shaper 2_5 passes on its 1 signal to the D-signal retarder 4_2. As the store 3_3 is in state 0, the signal, after a short delay, passes on to the output amplifier 5_3 and, via the OR gates 7_5, 7_9 and 7_{11}, arrives at the control inputs C_1, A_2 and C_2 of the analogue part. The drive reverses and at the same time the signal from 2_5 via the OR gate 7_2 resets store 3_1 to OFF.

If a normal stop command is given by pressing the button 10_3, the store 3_5 will be set at 1 via the pulse shaper 5_1. The transposing network 8 leads one of the two incoming signals from 2_2 or 2_5 to the output, depending on the control input at which a 1 signal is available. Since the transposing network acts at the same time as an inverter, the signals given are inverted.

At the moment the left-hand reversal point (indicator 1_1) is reached, a 1 signal appears at the output of the transposing network due to the position of 11. Thus the AND condition at the AND gate 6_2 is met. The signal passes through and, after amplification by 5_4, arrives via the OR gates 7_7, 7_8, 7_9 and 7_{10} at the control inputs B_1, D_1, A_2 and C_2 of the analogue part. This disconnects the desired-value store and resets the integrators. The store 3_5 is also switched off by 5_4, causing the signalling relay to cut out. At the same time the stores 3_2 and 3_3 are set to 1 by the signal from 5_4. The signal arriving in the meantime at 4_1 from 2_2 is thus not passed on, being delayed until it is switched on again.

On setting-up, the signals of the incoming pulse shapers 2_3 and 2_4 are passed direct to the analogue part via the switch 12, which is then closed, and the corresponding OR gates. On releasing the push-button, a 1 signal is produced at the inverted output of 2_3 or 2_4, which arrives via the OR gate 7_6 at the output amplifier for the stop signal. Suitable precautions ensure that all stores assume a definite state when the voltage is applied.

Following this functional description which shows the simplicity of the logical combination, it is interesting to compare the solution of a given switching programme by the Brown Boveri electronic system with a possible solution using the conventional relay techniques.

The basic considerations which led to the choice of the contactless electronic method are as follows: The switching times of relays and contactors, with their inherent scatter, are disturbing for reversal control, which must of necessity be precise and rapid.

The numerous switching operations and the large number of continuously moving contacts considerably increase the likelihood of breakdown due to wear. The modern electronic units employing semiconductors offer a far greater level of reliability for this type of work.

Taking the investment in equipment into account, the number of basic elements used is larger than the number of relays necessary. However, since the basic elements are in practice combined to form larger units (functional groups), the outlay for the remainder of the equipment can be reduced to a minimum.

Numerically Programmed Pick-Feed

Because of the discontinuity of the working motion only the principle of step or pick-feed can be applied to planing and slotting machines. As a rule, the feed motion is derived directly from the working motion.

Nowadays, from extremely simple beginnings, mechanical devices for this have developed into real miracles of precision. The reason is the desire for finer and more accurate feeds, simpler operation and setting, as well as partial automation. A pick-feed motion is also used frequently for profile and copy milling machines. Here, too, a variety of designs for mechanical and hydraulic operation are to be found. With these a considerable outlay is necessary, especially for the dosage and remote control.

With the help of the Brown Boveri electronic system, it has now become possible to make an electrical pick-feed system which functions without contacts and, while accurate and capable of fine feeds, can also be fitted to practically any machine. It works with a d.c. motor or a three-phase twinstop motor. The rate of the feed is set on the control desk with manual dials marked in decimals, either direct in mm or parts of a mm. The principle employed is that of a numerical positioning system.

Fig. 5 shows the block diagram of a numerical pick-feed control system as used for a small planing machine. The spindle which moves the crosshead is driven via a reduction gear 3 by a d.c. shunt-wound motor. The rotor is switched on and off by a switching amplifier with direction reversal and equipped with power transistors. The feed motion is measured directly on the spindle by means of pulse pick-up. This works on the principle of the oscillator position indicator, i.e. completely free from contacts. The signals coming from it are passed via a pulse shaper 5 to a pulse counter with three or more decades. These binary-decimal counters, which for industrial use are equipped with special transistors, function up to a counting frequency of 100 kc/s. The coincidence circuit 10 compares the measured values with the values set on the selector switch 16 for setting the feed amplitude.

If they coincide, the output signal from 10 changes the store 8 to state 0. This closes the switching amplifier 12 via the OR gates 9_1 or 9_2 and the drive motor is switched off. At the same time the change of state of the store from 8 via the one-shot multi-vibrator 7 resets the counter to zero. This takes place considerably faster than the rate at which the measuring pulses can come in. Until the motion is effectively stopped, the counter continues to register the incoming pulses. The overrun, resulting from the inertia and other characteristics of the whole system, is measured in this way and stored in the counter. The overrun registered at the previous feed step causes the next stop order to be given that much earlier. The first feed step will

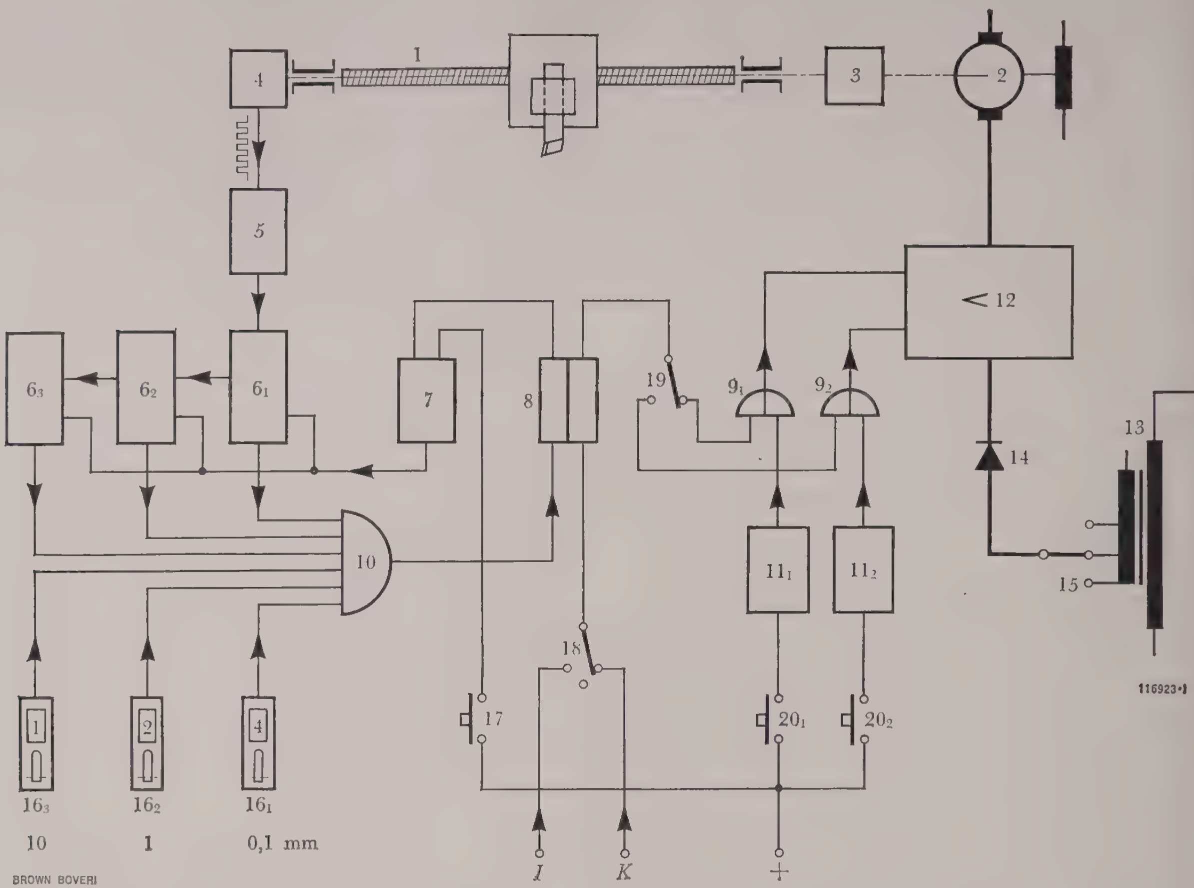

Fig. 5. – Functional circuit diagram of the numerically controlled and contactless pick-feed system, as applied in practice to a small planing machine

1 = Feed spindle
2 = D.C. drive motor
3 = Reduction gear
4 = Pulse generator on feed spindle
5 = Pulse shaper
6 = Pulse counter
7 = One-shot multivibrator
8 = Store
9 = OR gate
10 = Coincidence circuit
11 = Input pulse shaper
12 = Switching amplifier with reversal
13 = Isolating transformer
14 = Silicon power rectifier
15 = Switch for coarse speed stages
16 = Code selector for setting the feed amplitude
17 = Push-button for zero setting
18 = Selector switch for feed after cut or return run
19 = Selector switch for feed direction
20 = Push-buttons for manual control

therefore exceed all those following by the amount of the overrun. However, as this is almost always given as a starting step, it is of no practical importance. All mechanical and electrical irregularities of the drive system, such as may occur during service, are compensated as far as possible.

The feed motion is switched on by the synchronizing signals coming from the digital control part of the working motion. By means of the switch 18, the beginning of the feed can be set to the end of either the forward or the return motion. For setting-up or rapid traverse, the drive can be controlled by push-buttons.

The practical applications described in this article and taken from the wide field of control techniques show that the majority of the problems involved can be solved with the aid of the Brown Boveri electronic system. The project engineer has to ensure that the

specified conditions are fulfilled in accordance with the laws of electronic switching techniques, since it is not possible merely to transfer the principles which were previously valid for relay techniques, simply by replacing the contacts by contactless elements. The electronic system which Brown Boveri use and, perhaps equally important, the complete standardization which has already allowed most of the problems to be solved by simple combinations of standard components, simplifies and reduces this project work enormously.

(SL) F. GLANTSCHNIG

A NEW DIGITAL MEASURING, POSITIONING AND PROGRAMMING DEVICE WITH PUNCHED-TAPE CONTROL FOR MACHINE TOOLS

621.9–52

In an earlier issue[1] of this journal a newly developed electronic measuring and positioning device was described for the first time. In the meantime this device has been improved and extended, one innovation being the incorporation of punched-tape control for introduction of the program. The present article describes the design, principle, electric circuitry and applications of this transistorized unit.

NOWADAYS ELECTRICAL elements are being stipulated to an increasing extent for the operation of machine tools. They have to function automatically to compensate for the shortage of skilled workers, at the same time increasing the output and improving the accuracy of the workpiece. Among the operations which have to be performed are, for instance, the measurement of machine movements, either as distances or angles of rotation, and the preselection and storage of definite values, though this in itself is quite an old problem. Up to now optical devices were mainly used, with which precision scales could be read very accurately, but which provided no facilities for preselection or storage. For these additional mechanical devices were required, on which the desired length or angle could be set by means of stops. But allowance has to be made for the unavoidable inaccuracies in the transmission system, which become quite appreciable—sometimes inadmissibly so—when long distances are involved. Another possibility is to employ magnetic storage of points to which the machine part has already travelled, although this necessitates the execution of the programme once to obtain all the settings. Owing to the unavoidable number of intermediate measurements, this process may possibly take up considerable time. When the machine has to be set up for small quantities this process is likely to be too expensive. The ideal conditions, i.e. the precise determination in advance of a positioning and working program which will subsequently be continued automatically is therefore by no means attained by this method. Devices are desirable which perform both measuring operations and programming functions. It should be possible to make the settings in advance, merely from a drawing.

Having realized this necessity, the following device was constructed, representing an important step towards automation of machine tools, in which capacity it has to fulfil the general stipulations made regarding automatic apparatus.

[1] F. GLANTSCHNIG: Electronic Servo-, Programming and Positioning Systems. Brown Boveri Rev. 1957, Vol. 44, No. 11, p. 488–96.

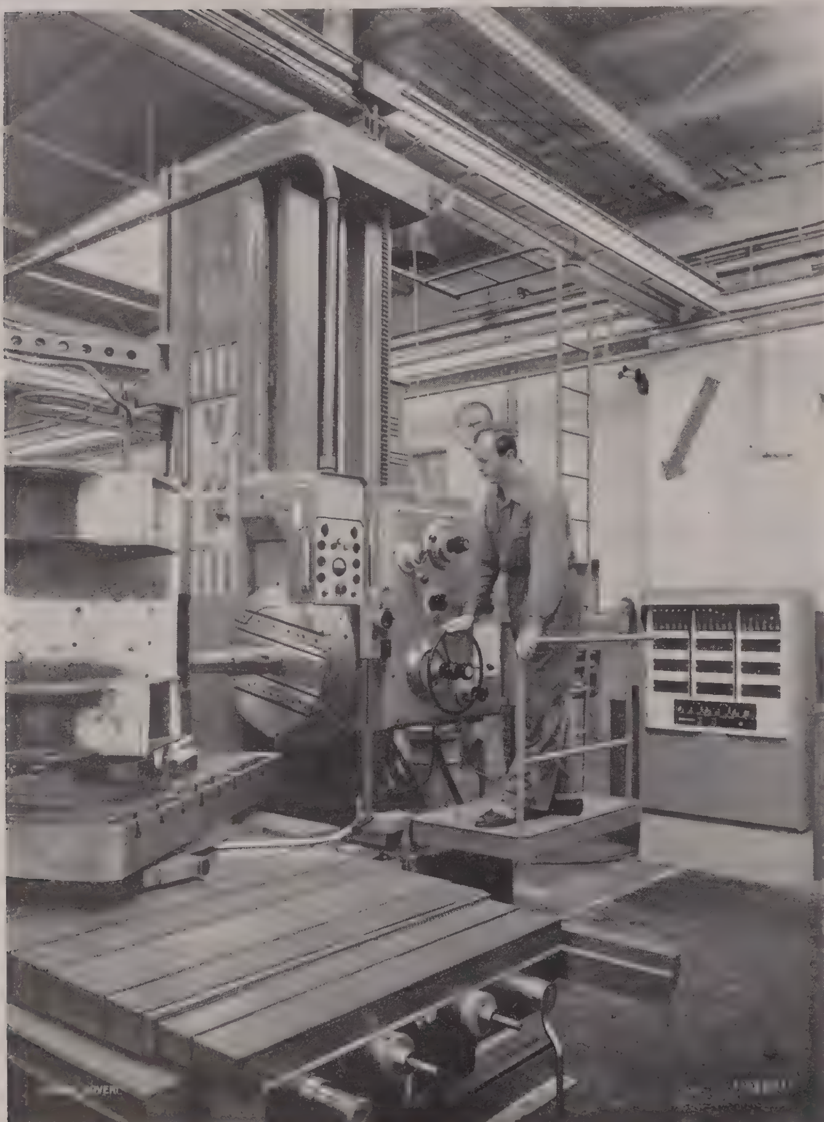

Fig. 1. – Horizontal boring machine with universal clamping table, equipped with

A digital measuring and positioning device for raising and lowering the headstock, transverse or longitudinal movement, by the table, changeable to circular movement.

Automatic measurement, forwards and backwards, by precision rack-rods and pinions on to optical digitizers with a resolving power of $^1/_{100}$ mm in the linear coordinates and 6 angular seconds in the polar coordinates of the rotary table.

This unit has been in operation for over a year in the Company's own workshops in Baden. The saving in working hours amounts to about 30%, so that the extra outlay has soon been amortized.

Choice of the Basic Principle of Electric Measurement

Fundamentally there are two methods of measuring distances electrically and fixing working points:

Using *analogue* principles, based on a voltage difference between desired and actual value, and by *digital* methods, for which the quantity to be measured is divided into a proportional number of pulses, which are counted and the result compared with a given number.

Both systems have their advantages and disadvantages, but for this particular application the digital principle is more favourable, for the following reasons:

The incoming measurements can be indicated almost direct.

Lengths of almost any size can be determined exactly; the units can be employed on very large machines without distances having to be divided up, and with very little additional outlay.

The processing of data to provide program functions is easily performed.

The general trend towards the adoption of the digital principle is also apparent in other fields. The

unit with punched-tape control, which was primarily intended for use on large machine tools, was therefore designed to employ digital methods, It has already proved successful in a somewhat simpler form (Fig. 1).

What Functions Does the Unit Perform?

The unit described performs the following functions:

- Measurement of straight-line movements of any length;
- Measurement of angular functions;
- Picking off measurements via precision rack-rods or spur rims with the assistance of photo-electric digitizers with a resolving power of $^1/_{100}$ mm in the linear coordinates and 6 angular seconds in the polar coordinates, for adjustment speeds up to 12 m/min;
- Correction of error in the rack-rod by addition or subtraction of pulses;
- Separate large-scale indication of the measurands with the aid of projectors;
- Introduction of programs by means of an 8-track punched tape, or by hand with decade switches on a control unit;
- Automatically calculated lead in terms of the preceding adjustment speed of the machine part.

Determining the Measurement on the Machine

Repeatedly the question arises of what system is most suitable for correctly measuring the distance and maintaining it without loss of precision. In this respect a wide variety of attempts have been made, some using purely optical methods, others with mechanical or magnetic systems, or combinations of two systems. When deciding which system to adopt, it is important to take into account where the system is going to be employed, and to what extent it is exposed to external influences.

For the unit described, which is mainly intended for use on machine tools, it was decided that a rack-rod or spur rim (for angular motions) would be the most suitable means of determining the dimension, in conjunction with a photo-electric digitizer. Here it was taken into account that the machine builder can handle such elements, with which he is well acquainted; furthermore, that the manufacture of a good rack-rod or spur ring, and its accurate assembly with a machine part do not present any insurmountable problems nowadays. In view of the small torque required for the digitizer, wear is practically negligible. A certain insensitivity to normal dirt also favoured the selection of this method.

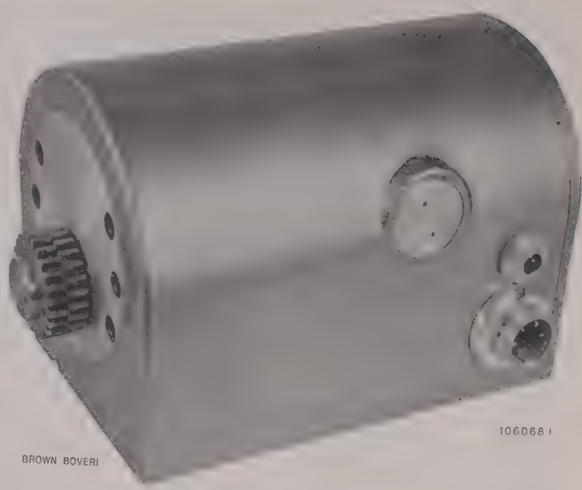

Fig. 2. – Digitizer for the electronic measuring and positioning unit

This digitizer, which attains an extremely high accuracy, operates with a rack-rod or spur ring marking the position, in conjunction with a special photo-electric digitizer with a resolving power of 100 impulses per mm.

The *digitizer* itself (Fig. 2) is a self-contained unit. On its drive shaft there is a two-part pinion, the two halves being sprung against one another to enable them to engage in the rack-rod without backlash. The pinion drives a graticuled disc mounted on a shaft in precision bearings. The raster of this disc is such that for every 0·01 mm distance travelled by the pinion a pulse is generated in the subsequent rotation unit. The raster of the disc is read off by two systems, each comprising a lamp, auxiliary raster and photo-diode. The two systems are mutually displaced in such a manner that, from the phase difference between the diode currents, the unit is able to determine the direction of rotation.

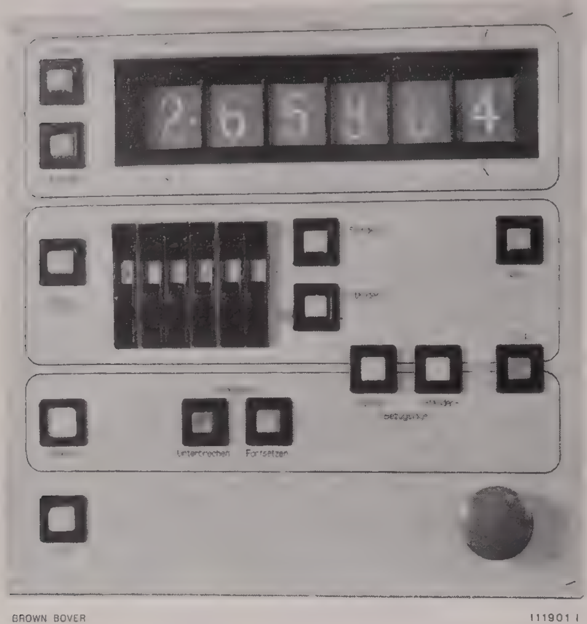

Fig. 3. – Control panel of a horizontal milling and boring machine equipped with a measuring, positioning and programming device controlled by punched tape

At the top of the unit is the indicator, which shows the measurement in large figures; below it the decade selector switches with numerical markings, on which individual dimensions can be pre-selected by hand.

Correction Circuit for the Rack-Rod or Spur Ring

Theoretically it would be simplest to utilize a first-class rack-rod or spur ring with the accuracy of a precision scale for picking off the dimensions. But, as everybody knows, the manufacture of such elements is an expensive business and for long lengths considerably increases the outlay for the equipment. Ways and means of reducing this cost have therefore been sought. Since the digital system allows pulses to be added or subtracted at any time, the correction of possible inaccuracies in the pick-off has been transferred to the counting system. A normally cut rack-rod with conventional tolerances is exactly measured after assembly with the machine, plus or minus errors marked, and the point in question fitted with specially shaped cams. The moving part of the machine possesses a pair of micro limit switches, which emit a positive or negative pulse for the counting system every time the cam passes over a switch, in accordance with the direction of rotation and the necessary correction, thereby influencing the count in the desired manner. The reliable correction is obtained with very inexpensive equipment. Even if dimensional errors should arise later, they can be corrected in the right sense at any time by adding further cams or displacing the existing ones.

Control Unit with Indicator and Decade Manual Selector Switches

The design of the control panel for the unit is illustrated in Fig. 3. This can be mounted separately on the most convenient control point of the machine so that the machine-minder can check the progress of work at any time. The numerical values are indicated in decades with digits from 0–9 by projector units, and are perfectly legible from quite a distance. Normally it is sufficient to have one indicator which can be switched from one set of coordinates to the next successively, although it is also possible to provide a separate indicator for each set of coordinates. Illuminated push-buttons are used for initiating and supervising the desired program function. For the manufacture of single parts, automatic control and introduction of the dimensions by punched tape can be dispensed with, the desired positioning points being given by hand by means of cleverly designed decade switches. Numbers marked on the switches then indicate the selected measurement direct.

Punched Tapes

For controlling machine tools punched tape is by far the most suitable of all known program carriers. It is cheap and reasonably resistant to dirt and handling by workshop personnel. Quite comprehensive programs can be accommodated on a roll a few centimetres in diameter, an advantage which must not be under-estimated when filing the programs is taken into consideration.

Fig. 4. – Photo-electric reader for an eight-channel punched tape

The Brown Boveri system employs eight-track punched tape 1 inch wide. Compared with the five-track tape commonly used for teleprinters this exhibits the following advantages: Six tracks instead of only five can be used to represent all letters and numerals. This obviates the necessity of inserting a special sign between letters and numerals, as in teleprinter systems. Evaluation of the information read off the tape thus becomes much simpler and more reliable.

A further track is used to enable a faulty read-out on the other six to be recognized immediately and the execution of any other operations blocked. This is the main advantage over the five-track tape, on which incomplete punching or damage, as well as dirt on the tape or in the reader may cause a faulty read-out without this being recognized. This can of course have disastrous consequences for the workpiece and/or the machine. The check is made on the principle employed in computers, where the check track is punched each time the number of holes in the other six tracks of one symbol is even. Thus the total number in the 6+1 tracks is always odd. This criterion is employed for reading out every symbol, before the content of the latter is passed on to the control system. The probability of two holes of one symbol being wrong at the same time is so small that it does not even have to be taken into account in computers.

The last track is reserved exclusively for stamping a special end symbol. It marks the end of a block of instructions, as will be described later.

The tape is produced on machines of the Flexowriter type, such as are used for book-keeping and administrative tasks. These are so designed that they can punch the tape, at the same time typing out in clear; the tape can also be read and duplicated. Furthermore they allow stereotype parts of the program (head and finish) to be punched out semi-automatically.

The reader (Fig. 4) operates photo-electrically and therefore contains no parts exposed to wear or needing periodical attention. The tape is fed through by a drum and back-pressure wheel, which facilitates insertion and eliminates the possibility of the tape being damaged by a pin-wheel. The reading speed is so high at 80 symbols per second that the time taken in reading is negligible compared with that for the shortest movement.

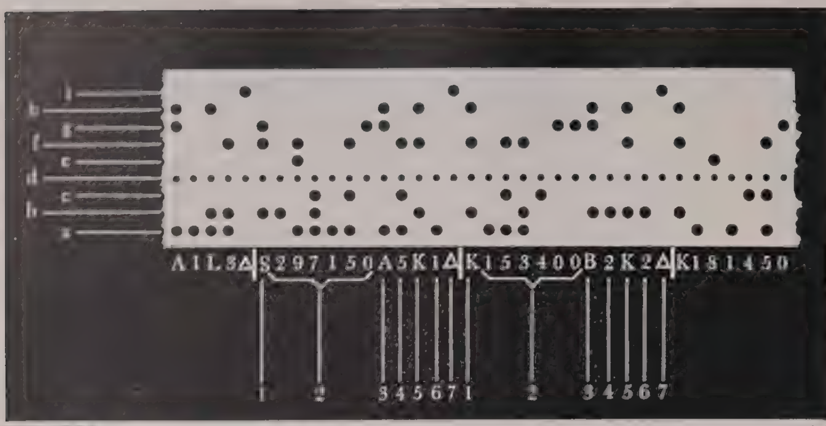

Fig. 5. – Section of a punched tape

1 = Coordinate
2 = Coordinate value
3 = Gear stage
4 = Speed
5 = Clamp
6 = Program instructions
7 = End symbol
a, b, c = Channels 1, 2, 3
d = Feed channel
e = Channel 4
f = Channel for check perforations
g, h = Channels 5, 6
i = Channel for end symbol

Programming

The instructions to the machine, which in their entirety form the program, are arranged as groups of symbols, or blocks on the tape. One block always contains all the instructions for positioning one coordinate, in the following order (Fig. 5):

One symbol (number or letter) indicating for which coordinate (pillar or table motion) the subsequent instruction is intended;

The value of the position to be entered in the particular coordinate, in the form of a set of numbers:

A group of symbols indicating at what motor speed and in which gear stage this position must be approached;

One or more symbols controlling various auxiliary functions, e.g. clamping the guides, shutting off or switching on the cooling water;

One symbol representing instructions for continuation of the program (e.g. interruption, continuation as soon as preceding instructions have been executed, unconditional continuation, etc.);

One end symbol.

Since the end symbol has a channel reserved for it, the blocks stand out clearly on the tape. The arrangement in the correct order and organization of the instructions simplifies the preparation of the program as well as the search for and recognition of arbitrary digits on the tape. This is particularly appreciated when slight modifications have to be made to the program owing to changes in design or in the operation. Then it is merely necessary to cut out the sections concerned from the tape and replace them.

Course of the Program with Punched-Tape Input

The course of the automatic program is depicted in Fig. 6, which applies to a control system in two coordinates, e.g. movement of the pillar and headstock of a boring machine. On receipt of a signal from the program control the reader reads the next block off the tape. The output signals of the reader are checked in a test circuit for errors, with the aid of the perforations provided for the purpose. The first symbol of the block controls the circuits in the distributor so that the subsequent symbols are conveyed to the stores of the corresponding coordinates. At the end of this read-out the store 10a contains the value of the position to which the machine has to run, store 11a the symbol for the speed and auxiliary functions. The symbol for further action is always conveyed to store 19.

The successive measurement of the actual position is the task of the digitizer, whose impulses, following the determination of the direction of rotation, are added to those of the correction circuit by the counter. The counter 1a thus indicates the position

1a, 1b = Recorders
2a, 2b = Directional discriminators
3a, 3b = Correction circuits
4a, 4b = Gear trains
5a, 5b = Correcting units for gear
6a, 6b = Drive motors
7a, 7b = Correcting units for motors
8a, 8b = Counters
9a, 9b = Control units
10a, 10b = Stores for coordinate values
11a, 11b = Stores for feed and auxiliary functions
12 = Distributor
13 = Punched-tape reader
14 = Test circuit
15 = Decade switch
16 = Pillar drive
17 = Headstock drive
18 = Indicator
19 = Program control

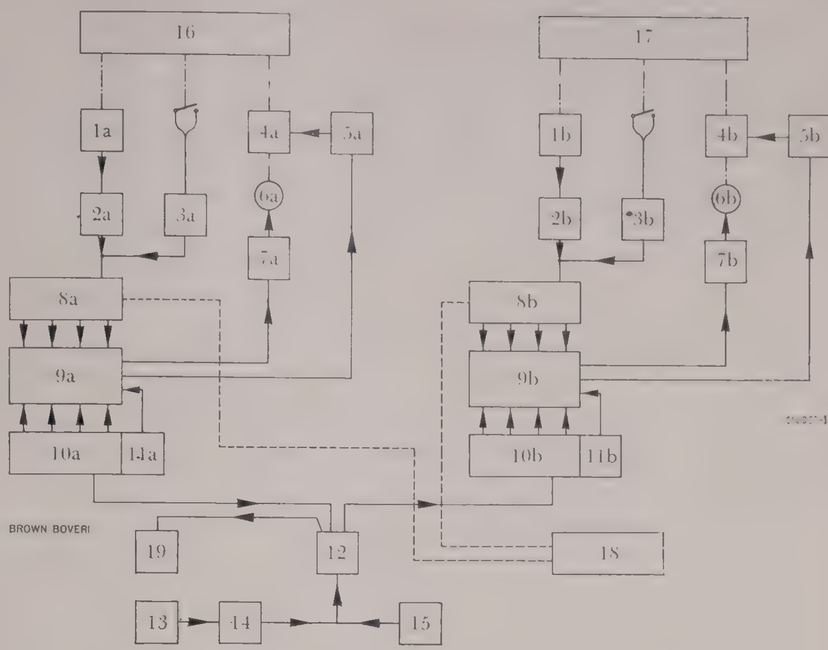

Fig. 6. – Block circuit diagram of a device for two coordinates

of the pillar relative to a zero point set at the beginning of the operation.

From the numbers in the counter and stores *a* the control units determine the direction in which the pillar traverse motor must rotate. In accordance with the content of store *b* it actuates the couplings of the transmission through correcting units and brings the motor up to speed. It also calculates the counter positions corresponding to those points on the path travelled, at which the speed of the motor has to be reduced or the gear changed, so that the pillar can be brought at decreasing speed and finally at the creeping speed into the programmed coordinate value. This is accurately achieved in a very short time, regardless of what position the pillar, for example, occupied previously.

Continuation of the program depends on the instructions contained in the block and on operation of the buttons "Interrupt-Continue" (Fig. 3). Depending on the instructions received, the program is either interrupted at predetermined points, for example to allow for tool changes, or the machine-minder can interrupt the program at other points, in order to carry out an inspection of the workpiece or to remove swarf. In an emergency (tool breakage) the machine can be stopped immediately by pressing a "Stop" button.

Before machining can commence, the zero point must first be determined, from which the positions of the pillar and spindle are measured. For this purpose the workpiece is replaced by a telescopic sight or point, and the machine brought into a reference position by hand control. The counter reading corresponding to this position is first transferred from the punched tape into store 10. On arriving at the reference position a button is pressed, causing the content of this store to be taken into the corresponding counter. A separate button is provided for each coordinate, so that the marking lines on the workpiece do not have to overlap one another.

By the method described it is possible to fix the zero point relative to the workpiece, without risk of error. When the workpiece is clamped up it merely has to be aligned parallel to the axes of the machine. If several movements have to be performed simultaneously, the blocks on the tape are read off direct, in accordance with appropriate instructions. The time required for this is so short that all motions

start practically together. This represents a considerable gain in time compared with manual operation. The control system can easily be augmented to deal with any number of motions. The actual number is only limited by economic considerations. For example, it would be possible to include the spindle and milling-slide feeds.

Course of the Program with Hand Input

If the positioning points are introduced by hand, the punched tape is replaced, as already mentioned, by decade switches for insertion of the coordinate values, and buttons for selecting the coordinates. For the speeds the controls provided in any case for manual operation are used. When the "Start" button is pressed, the coordinate values are conveyed to the store in the same manner as with tape, and positioning carried out.

The task of the machine-minder is confined to insertion of the numerical values and supervising subsequent operation. If necessary, positioning can be momentarily interrupted by pressing the "Stop" button. The value of the reference position is likewise set on the decade switches and transferred to the counters by pressing the appropriate button.

Positioning with values introduced by hand is straightforward and can be supervised by watching the essential indicator, thus largely eliminating errors.

Supply

The counters and associated circuits are fed from a buffer battery, which is capable of continuing the supply for one hour in the event of a mains breakdown. This prevents the contents of the counters from being lost if the supply fails, which would necessitate determining the zero position all over again. Since the power involved is only a few Watts, resulting from the exclusive use of transistors, the battery does not represent an excessive outlay.

Conclusion

Summarizing, the main features of the device described are as follows:

- Automatic positioning from punched tape,
- Individual positioning if desired, by manual preselection,
- Measurement and numerical indication of the coordinate values.

These properties permit the device to be employed on machine tools of all kinds and sizes, whether they are used for mass production or for complicated single objects. In view of the tendency for automation to expand, this versatile unit is sure to attract increased demand in the future.

(KME)

A. SCHENKEL
M. MORGENTHALER

DIGITAL TELE-OPERATION EQUIPMENT EMPLOYING SEMICONDUCTORS

621.398:621.382

CONTACTLESS remote-control systems and the cyclic code telemetering equipment are typical examples from the tele-operation range. Remote control and telemetering are the main means of transporting information in the sphere of the production and distribution of electricity, as well as other forms of energy, such as oil or natural gas. In many other manufacturing processes they also play a vital role.

The conception of such equipment arises out of requirements which nowadays are being stipulated in an increasingly concrete form as regards remote-control techniques. These requirements can be characterized in the following manner: As remote control finds its way into installations of higher responsibility grades, growing demands are made regarding the extent of flow of information, speed of transmission and reliability.

On the other hand, little is gained by transmitting a large quantity of information if that information cannot be arranged to make sense. Up to the present, direct indication, including recording, has always been in the foreground, while decisions regarding actions to be performed are still left to man, for the most part.

It is impossible to afford effective relief to the operating staff without the incoming information having to be processed to a greater extent. This is the point at which the digital techniques described in an earlier article[1] take on as over-riding system. The tele-operation units, e.g. telemetering or remote-control equipment, then tend more to act as input or output units, part of the information still being indicated direct, but the remainder can be utilized for direct open or closed-loop control tasks, with complete exclusion of the human element, by logical relations and processing in a special computer.

Information in code form is most suitable for processing in this manner because it does not suffer losses. This is one of the main reasons why tele-operation techniques employing the digital principle already demand, and will continue to demand increased attention.

[1] A. DE QUERVAIN: Digital Information Processing. Brown Boveri Rev. 1959, Vol. 46, No. 11/12, p. 609–28.

The Digital-Cyclic Telemetering System

621.398:621.317

The digital-cyclic telemetering system described in this article is composed mainly of semiconductors; only a few auxiliary circuits contain miniature cold-cathode tubes. With a bandwidth of 360 c/s the transmission speed is 20 measurands per second. The system can be expanded to handle up to 36 measurands. The measurement current of 0–5 mA fed in at the transmitting end is reproduced with the same range at the receiving end. The accuracy is better than $\pm 0{\cdot}5\%$. Hence the error of transmission is less than the classified error of conventional indicating instruments. A telemetering system of this kind fulfils the present intensified requirements regarding the number of measurands which can be transmitted and the accuracy of measurement.

THE CYCLIC telemetering system which Brown Boveri have employed for over 10 years for the transmission of measurands over wire, by radio or power line carrier channels, has proved extremely successful, especially as regards accuracy, reliability of transmission and economy.

The measurands are transmitted as brief groups of audio frequencies, staggered with respect to time and emitted in immediate succession. The system is based on an analogue principle, in that a change in one measurand corresponds to a proportional change

in the a.f. group allocated to it. The equipment used for transmission was designed on conventional circuits employing electron tubes [1, 2].[1] The semiconductor elements which are now available allow new methods to be adopted with the aid of digital techniques [3].

In contrast to the analogue methods which were previously employed, dealing with continuously variable quantities and relying on a comparison between these and constant reference values, digital techniques utilize quantities expressed as numbers which, with the aid of combinations of Yes/No states, are represented by a definite number of bistable circuits.

The quantity to be transmitted is allocated a definite number by means of a special circuit, known as an analogue-to-digital converter. The accuracy and linearity of transmission is determined solely by the resolving power and the stability of the conversion process. The number so obtained is subsequently coded with smaller or larger redundancy, according to the requirements of the transmission conditions, and emitted as a pulse train.

Thus each group of pulses corresponds to one measurand. The greater the redundancy of the code employed, the larger the bandwidth required will be with equal resolving power and transmission speed. The redundancy of the code is a measure of the attainable reliability of transmission as regards line noise (see [4]). The bandwidth and the reliability of transmission can therefore be offset against one another in a digital system and the optimum selected for a particular set of conditions. The accuracy of the system is not in the least affected in so doing. That is not the case in an analogue system, e.g. the frequency-variation system. There the bandwidth is strictly related to the accuracy of transmission. In digital systems, on the other hand, where the speed of transmission is of minor significance, the bandwidth can be reduced to a minimum. When planning an installation, this may possibly lead to considerable saving on transmission equipment.

Another major advantage of the digital system is that storage of a measurand in the form of a code number is very simple and may be continued for any length of time without the accuracy suffering.

Finally, it is worth mentioning the ability to perform arithmetical operations such as addition, subtraction, and so on, with individual measurands, without any additional errors being introduced.

Design and Main Properties

Before proceeding any further it should be pointed out that the digital telemetering system employs exactly the same cyclic system of switching from one measurand to the next (scanning) as the rapid-cyclic system with frequency variation, as described in earlier articles [1, 2]. It also contains the following functional groups:

- The scanning chain at the transmitting end which switches the measurands through to the transmitter.
- The transmitter, in which the scanned measurand current is converted into digital form, the pulses being transmitted by a frequency-shift channel to the receiver.
- The receiver, which evaluates the incoming pulses and converts them into a parallel code-word, retained as a combination of Yes or No states of bistable circuits.
- The scanning system at the receiver end, which picks up all the Yes/No states offered by the receiver and conveys them to the code stores, also known as measurand registers.
- The synchronizing system, which firstly ensures synchronism between the timers, and controls the switching of various digital functional units in the transmitter and receiver, and secondly ensures that the two scanning chains are kept in synchronism.

The first of these functions is performed by amplitude modulation of the a.f. signal which is permanently present for transmission of the pulses. The clock frequency generated by the timer in the transmitter is transmitted in this way to the receiver, where it controls the timer at that end in synchronism. The second synchronization function is

[1] The figures in brackets refer to the bibliography on p. 740.

performed by a pilot code transmitted at the beginning of every cycle, which is shifted from the steady-state position to a specially provided value.

Scanning the measurand currents, normally of the order of 0–5 mA d.c., is performed by a special transistorized system which, regardless of external temperature influences, operates extremely accurately. A feature typical of this circuit is the unusually constant input impedance during the scanning process, which is essential as soon as electronic compensators are used as the source of current.

In contrast to the transmitting end, the measurands are scanned in code form at the receiving end. Here the conversion from digital to analogue form has to be performed separately for every measurand, using a specially developed electro-mechanical arrangement. Under normal circumstances the output current is of the order of 0–5 mA with a connected burden of not more than 5 kΩ.

Assuming all unfavourable external influences act at the same time, the linearity of reproduction of the measurand should be within ± 0·5%

Principle

Basic Channel

The system used to transmit a single measurand is referred to as the basic channel. It comprises the transmitting end, where the measurand is converted into a code signal suitable for transmission, and the receiving end, where the incoming code signal is converted back into a quantity which can be indicated by an ordinary instrument (Fig. 1).

The transmission of a measurand occurs according to a fixed schedule. The measurand is continuously fed to the coding device in analogue form. In an analogue-to-digital converter it is changed into a binary number proportional to the original value. The eight digits of the binary number are obtained at regular intervals and stored as on/off states of bistable circuits. In a further sequence the information is read out of the store and transmitted. For this the frequency-shift principle is employed as it assures maximum freedom from line noise and other disturbances.

Pulses and gaps appear as audio frequencies f_1 and f_0 in the message. At the receiving end they are converted into corresponding voltages by means of a frequency discriminator and stored in a preliminary store.

Fig. 1. – Block diagram of the basic channel

1 = Measurand detector
2 = Coding system
3 = Transmitter
4 = Receiver
5 = Decoding system
6 = Indication of measurand
A = Measurand current (d.c.)
B = Measurand in code form
C = Transmission of code-word
D = Word
E = Measurand current (d.c.)

To prevent false readings from being indicated at the receiving end, despite the possibility of noise, the transmitted pulse train is extended by one digit, for check purposes. It thus has a certain redundancy. The exact manner in which this check is performed will be described later. If this check of the code signal—or word—which now consists of nine digits, proves it to be correct, it is transferred from the preliminary store to the measurand store, all digits simultaneously. If the nine-digit word is wrong, the information is not transferred by the preliminary store but cleared and the store reset. The word from the previous cycle, still in the measurand store, is held there until the next transmission takes place. With each transmission the preliminary store is emptied and prepared for the reception of the next word. The measurand store, which holds the measurand in code form from one cycle to the next, controls the digital-to-analogue converter. The latter emits a current corresponding to the stored word, and thus proportional to the transmitted measurand.

Program Timer

The program, according to which the various switching operations and logical decisions have to take place to transmit a measurand in digital form, is dictated by the program timer. This determines

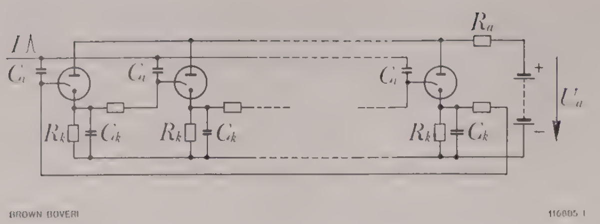

Fig. 2. – Principle of a counting ring with cold-cathode tubes

R_a = Common anode resistance
$R_k C_k$ = Time-lag elements
C_i = Coupling capacitors for firing pulses
I = Firing pulses
U_a = Anode voltage

and measures the time which ought to be taken to transmit the nine-digit word from the transmitter to the receiver. Since one measurand transmission is immediately followed by the next, this time measurement has to be continually repeated.

The program timer consists of a constant-frequency oscillator, a pulse shaper, and a chain of binary counters. From the wave-train emitted by the oscillator the pulse shaper produces pulses, which are counted out as a time unit by the counters, consisting of rings of cold-cathode tubes.

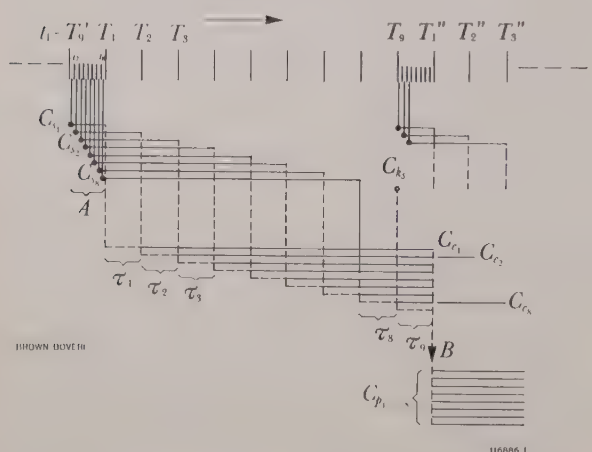

Fig. 3. – The sequence from formation of the code at the transmitting end to storage of the code at the receiving end

$t_1 - t_8$ = Timing of first ring
$T_1 - T_9$ = Timing of second ring
A = Generation of code digits
$C_{s1} - C_{s8}$ = Code digits of the binary measurand word, stored at the transmitting end
C_{ks} = Check digit (ninth code digit)
$\tau_1 - \tau_9$ = Transmission of code digits
$C_{e1} - C_{e8}$ = Code digits held in the preliminary store at the receiving end
B = Transfer of word from preliminary to measurand store
$C_{p1} - C_{p8}$ = Code digits held in measurand store

The counting ring in Fig. 2 is notable for the fact that with every firing pulse passed on, one tube fires while the preceding one is extinguished. The fired state thus progresses right round the cycle in the rhythm of the firing pulses, and then the next cycle starts. The number of times the first ring is traversed can be determined by a second ring. A means is provided by which the first ring imparts a pulse to the second at the end of each completed round, thus advancing the second ring one stage each time.

In this manner the pulse program illustrated is produced, consisting of two separate pulse trains t_1-t_8 and T_1-T_9. The former is used to control the analogue-to-digital conversion, and the latter for reading out the digits obtained by the conversion, and to mark the rhythm of transmission. The analogue-to-digital conversion takes place nine times as quickly as the other operations. This results in two distinct advantages; firstly, the error in measurement, which may occur during the conversion from analogue to digital form (because the currents being measured are not steady, but may be varying all the time), is reduced to a minimum, and secondly, the conversion of the next measurand can coincide with the transmission of the check pulse T_9. Hence there is hardly any dead time in the transmission.

At the receiving end the fastest action is keying in the incoming code pulses into the preliminary registers. This must take place in synchronism with the emission of the code pulses at the transmitting end. Hence the nine-digit scanning ring at the receiving end must be synchronized with the second ring at the transmitting end. The synchronization criterion needed for this is obtained, as mentioned already, simply and continuously by amplitude modulation of the frequency-shift signal.

The synchronism of the counting speed is guaranteed by evaluation of this amplitude modulation in the receiver. Synchronizing their starting, however, is not assured by this means. The method adopted for this is described in a separate chapter.

Analogue-to-Digital Conversion

The converter employed for this requires the measurand in the form of a direct current. The possible sources are, for instance, a measurand transducer operating on the compensator principle, or a rectifier. The current input into the analogue-to-digital converter is matched to the output currents of the commonest types of compensators, and is of the order of 0–5 mA. It can, however, be adapted to direct currents up to 10 mA.

In the analogue-to-digital converter the digital value corresponding to the analogue input value is determined in steps, 250 digitizing steps of 20 μA corresponding to a current range of 0–5 mA. Thus the maximum attainable accuracy of conversion is $\pm$ 0·2%.

In digital techniques it has proved most convenient to express a number, in this case a number of digitizing steps, as a sum of different powers of two, employing bistable functional units. Such units (bistable circuits containing transistors, glow tubes, tunnel diodes, etc.) can represent any binary number, depending on their order and state. With eight such bistable units it is possible to represent numbers from zero to 250. The number 250, for instance, is composed of the following terms:

$$1 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$

from the arithmetical sum

$$128 + 64 + 32 + 16 + 8 + 0 + 2 + 0 = 250$$

If the state of the bistable units allocated to the various binary powers is denoted by L for on and 0 for off, the number 250 can be represented in digital form by LLLLL0L0.

With eight bistable elements and the allocated binary graduated currents, it is thus possible to represent the measuring range in digital form with an accuracy of $\pm\,{}^1/_{500}$ of the maximum current. The task of the analogue-to-digital conversion is now to find the number of binary graduated currents which go to make the input current, to an accuracy of less than the smallest current step.

The procedure for solving this problem can be likened to weighing an object on a pair of scales. The input current is comparable with the object to be weighed and the binary graduated currents correspond to the weights laid in the pan. In the conversion from analogue to digital form the addition or removal of a weight corresponds to switching comparison currents on or off. The task of the balance is performed by a device which compares the currents, known as the comparator. It switches off a current utilized for digitizing but found too high. The comparator has a sensitivity threshold amounting to 50% of a digitizing step, i.e. 50% of the smallest binary step. For a range of 0–5 mA this represents 10 μA. Hence the accuracy for the entire analogue-to-digital conversion is $\pm\,{}^1/_{500}$ of the maximum current.

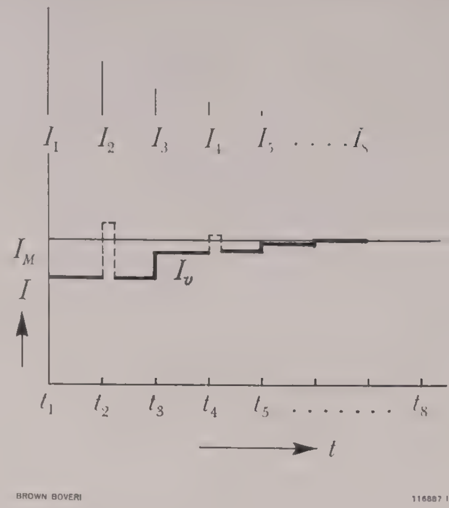

Fig. 4. – Digitizing a measurand current

$I_1 - I_8$ = Binary currents
I_M = Measured current
I_v = Comparison current obtained by combining the binary currents
$t_1 - t_8$ = Times at which respective binary currents are switched on
I_2, I_4 = Binary currents switched off again

The digitizing process (which consists of eight separate weighing processes) for the input current is controlled by the first counting ring, described previously. Fig. 4 shows the curve of digitizing a measurand current. The eight binary graduated currents are each switched through a gate which itself is controlled by bistable circuits. The eight bistable circuits are combined to form a register, their sequence corresponding to the graduation of the comparison currents they control.

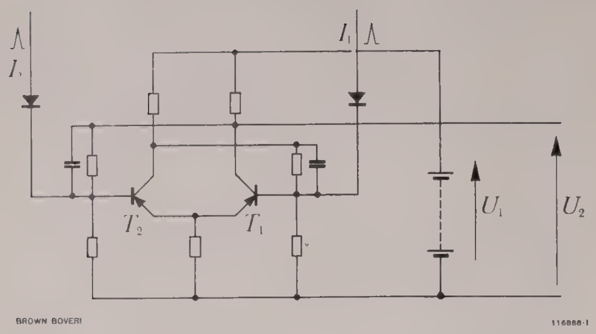

Fig. 5. – Binary counter of the store

I_1 = Closing pulse
I_2 = Opening pulse
U_1 = Battery voltage
U_2 = Output voltage controlling current switch
T_1, T_2 – Transistors

The input current (analogue measurand) is now compared a step at a time with the eight binary graduated currents by the comparator, and the result of the comparison held in the register. Thus at the end of the conversion from analogue to digital form this register contains a number, built up in a binary code from "On" or "Off" states of bistable circuits, and corresponding to the input current. A binary counter forming part of the 8-digit register, and made of transistors, is shown in Fig. 5.

Code Transmitter

The eight digits of the word are graduated with respect to time, having been arranged in order of weighting, and read out of the above register (see

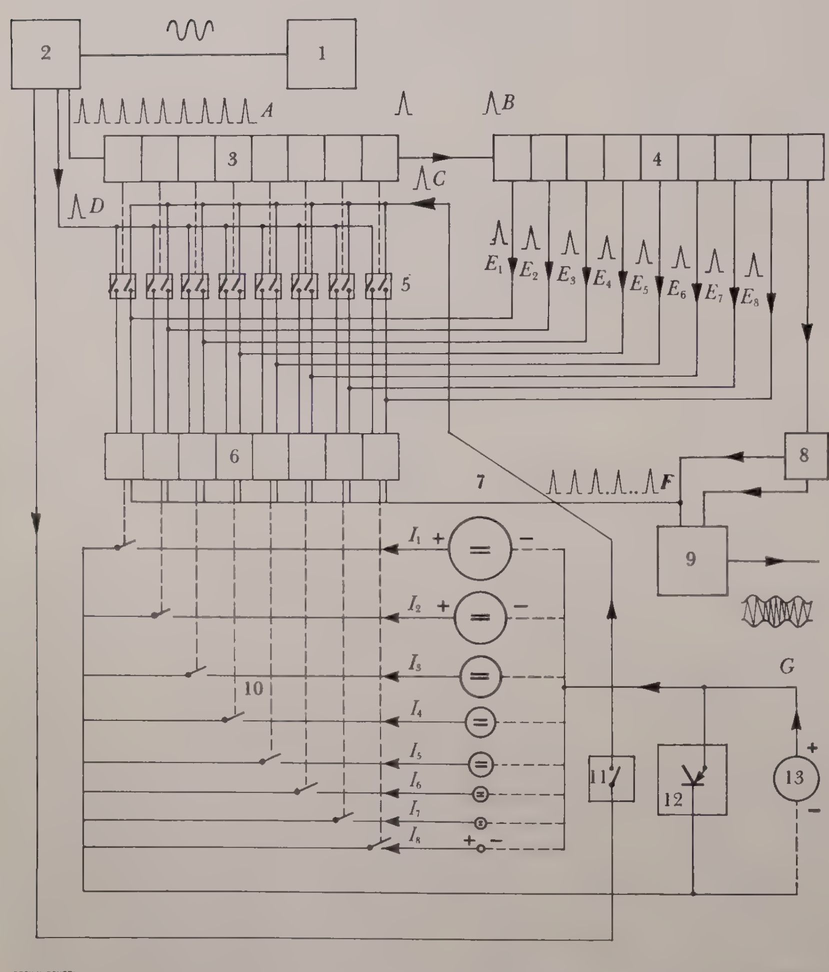

Fig. 6. – Block diagram of the telemetering transmitter

1 = Sinusoidal oscillator
2 = Pulse generator
3 = First counting ring
4 = Second counting ring
5 = Pulse gates controlled by first ring
6 = Stores
7 = Sources providing the binary currents
8 = Counts the "On" digits in the word and determines the ninth digit
9 = Frequency-shift transmitter
10 = Switches for the binary currents (controlled by the stores)
11 = Switches for the "Off" pulses to the stores
12 = Comparator
13 = Source of input current

A = Stepping pulses for the first ring
B = Stepping pulses for the second ring
C = "Off" pulses for the store
D = "On" pulses for the store
F = Code in the form of a pulse train
G = Transmitted signal
E_1 — E_8 = Pulses reading out code digits
I_1 — I_8 = Binary graduated comparison currents

Fig. 3). Following this action the store is reset, ready to take in the next code signal produced by the subsequent analogue-to-digital conversion.

The eight digits obtained by the conversion are now increased by a ninth, redundant digit, enabling greater reliability of transmission to be attained. Depending on whether the first eight digits—representing the measurand—contain an even or odd number of "On" states, the ninth digit will be allocated an "Off" or an "On" state, respectively. The nine-digit word therefore always has an even number of "On" states. At the receiving end the transmitted "On" states are counted to make sure they are even in number. If a word arrives with an odd number of "On" states, it must have been disturbed during transmission and is therefore not evaluated.

The first code transmission, as soon as it is complete, is followed by the second without any delay. This is made possible by coding the subsequent measurand during the time the ninth digit is being transmitted. The relationships between the individual functional units at the transmitting and receiving ends can be seen in Fig. 6 and 7.

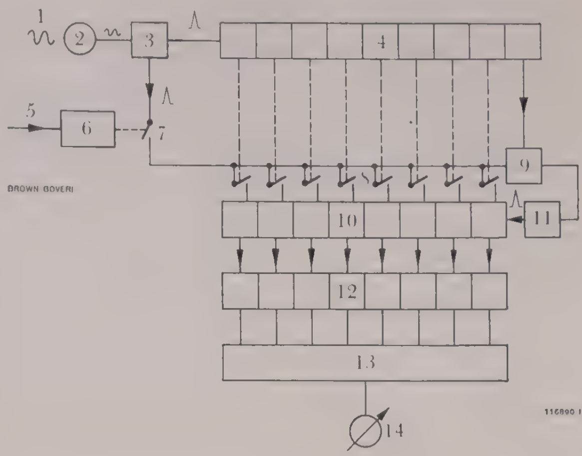

Fig. 7. – Receiving end of the basic telemetering channel

1 = Synchronizing signal
2 = Oscillator
3 = Pulse generator
4 = Scanning ring
5 = Received signal
6 = Phase discriminator
7 = Switch controlled by 6
8 = Switch controlled by scanning ring
9 = Counter for "On" states
10 = Preliminary stores
11 = Read-out pulse generator
12 = Measured store
13 = Digital-to-analogue converter
14 = Indicating instrument

Speed of Transmission

As already mentioned at the beginning of this article, the speed of transmission and the bandwidth of the channel are directly proportional to one another for a particular code. In most cases the bandwidth of the channel is stipulated in advance, so that the maximum number of code groups which can be transmitted per second is automatically fixed. Since each code group (i.e. measurand) consists of a definite number of changes of symbol, the system can be allocated a maximum transmission rate (expressed in baud). With more bandwidth it is possible to obtain a higher number of bauds. But there is a limit to the extent to which this increase can be taken, because transmission cannot be effected by keying a direct current, but by means of a shifted audio frequency. Should the available bandwidth be smaller, the necessary adaptation can be carried out by reducing the number of measurands transmitted per second.

Digital-to-Analogue Converter

In order to indicate the measurands with d.c. instruments the digital word held in the secondary store must be changed back into an analogue current. Each measurand store is therefore allocated a digital-to-analogue converter. Corresponding to the range of input measurand current at the transmitting end, the output current range for the digital-to-analogue converters is also made 0–5 mA. The internal resistance of the converter has to be sufficiently large to permit the connection of recording or indicating instruments with burdens up to 5 kΩ. For this purpose the converters are supplemented by a compensator in the form of an impedance converter. In principle, the digital-to-analogue converter with its compensator consists of a bridge circuit and an amplifier (Fig. 8).

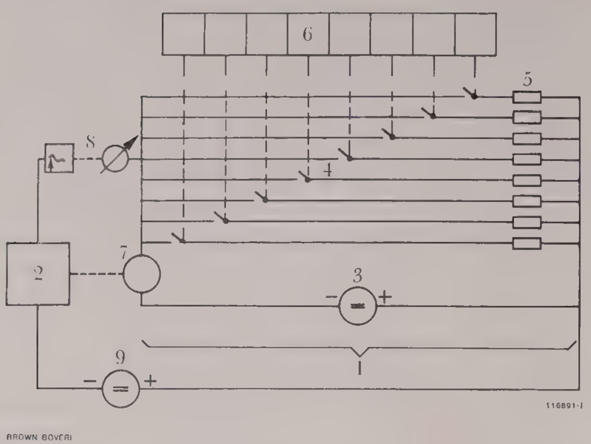

Fig. 8. – Schematic diagram of the digital-to-analogue converter

1 = Bridge circuit
2 = Current amplifier
3 = Constant-voltage source
4 = Switch
5 = Binary graduated resistors
6 = Measured store
7 = Galvanometer
8 = Indicating instrument
9 = Battery

A constant voltage is applied to one branch. In the opposite branch eight binary graduated resistors can be switched in or out from the measurand store. Between, in the measuring branch of the bridge, is a moving-coil galvanometer which controls the current amplifier in such a manner that the voltage drop in the resistance branch assumes the value of the constant voltage. By means of the binary graduated resistors eight currents are determined,

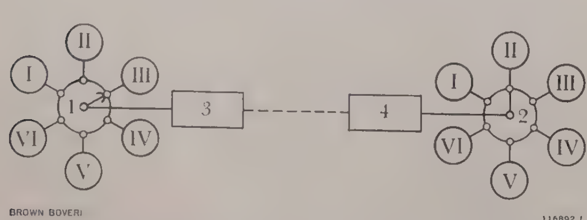

Fig. 9. – Block diagram of cyclic telemetering, 6 measurands

1 = Cyclic scanning system, transmitting end
2 = Cyclic scanning system, receiving end
3 = Transmitting end of basic channel
4 = Receiving end of basic channel
I–VI = Measurand points

which correspond to the binary currents in the analogue-to-digital conversion at the transmitting end.

Each binary counter of the measurand store controls a current corresponding to the stored value. Depending on whether an "On" state or an "Off" state is stored as code digit, the respective binary current is switched on or off. The sum of the currents switched on gives the measurand current.

The time constant of the compensator is a maximum of 0·1 s. The error in the digital-to-analogue conversion, due to the compensator, is negligible.

Scanning

A scanning system at the transmitting and receiving ends allows a series of several measurands to be transmitted successively over the one basic channel. From the block diagram of the cyclic telemetering system (Fig. 9) it can be seen that the scanning devices at the two ends act like stepping switches. The change from one measurand to the next is performed synchronously. It should be noted that the scanning device at the receiving end lags behind that at the transmitting end by one measurand because coding the measurand takes place during the transmission of the ninth digit of the foregoing measurand word. The two scanning systems are synchronized by a counting ring belonging to the program timer of the basic telemetering channel. At the transmitting end each measurand current is conveyed by a transistor circuit to the coder at a time determined by the counting ring, and converted into digital form.

The measurand currents are not interrupted by scanning and can still be used for indication or recording by d.c. instruments. For scanning, currents up to 10 mA are permissible.

At the receiving end the eight digits of the word are switched in order of seniority into the measurand stores by gates, there being a gate at the input to each store. The word is fed simultaneously to all gates, which are normally shut, and it can only enter the store whose gate is opened by the firing

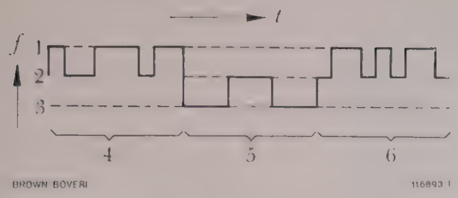

Fig. 10. – Transmitted measurand and synchronizing code

1 = Measurand working frequency
2 = Steady-state frequency
3 = Synchronization frequency
4 = Last measured word
5 = Pilot synchronizing code
6 = First measurand word

point of the counting ring. Shortly before switching over, the particular store is cleared and is thus ready to receive new information. This interruption only lasts a few hundredths of a second and does not affect the measurand in the least.

Synchronization

It has already been stated that the pulses at the receiving end are synchronized by a clock frequency transmitted as amplitude modulation. A second synchronizing signal is now required to ensure that the two scanning sequences are in phase with each other. This signal is emitted at the beginning of each measurand sequence. Once it has started, the sequence runs through synchronously until the last measurand. In view of its importance this special synchronization signal is transmitted in code form with a special frequency swing.

The oscillator can thus oscillate at three different frequencies, the middle one of which is known as the steady-state frequency. When transmitting the measurand word the oscillator is keyed between this frequency and a higher frequency. Having transmitted the last measurand, the oscillator is keyed to the special lower frequency to transmit the synchronizing signal. The result is the pulse program illustrated in Fig. 10.

At the receiving end the pilot synchronization code is checked in a synchronizing unit and a start pulse derived from it, to restart the scanning of the measurand stores.

Mechanical Design

Only semiconductors and cold-cathode thyratrons are used as active elements, thereby assuring long life. Since such functional elements do not have to be readily interchangeable, as was formerly the case with heated-filament tubes, these elements are now soldered direct to the plates of printed circuits, together with the resistors and capacitors.

Despite the extremely compact arrangement of the components, the use of printed circuits renders all parts easily accessible, since a plug-in printed circuit can be removed in next to no time. The unit is constructed of sub-assemblies and tiers in exactly the same manner as described in the article beginning on page 670.

Technical Data

Inputs at transmitting end	0 — 5 mA
Outputs at receiving end	0 — 5 mA
Accuracy of transmission	± 0·5%
Speed of transmission	10 or 20 measurands/s
Corresponding to a bandwidth of	240 or 360 c/s
Transmission level (r.m.s.)	max. 4·0 V on 600 ohms
Reception level (r.m.s.)	280 mV ± 8·7 db on 600 ohms, but at least 8·7 db above the noise level in the pass-band of the receiver filter
Supply voltage	20–28 V d.c.
Maximum capacity	36 measurands
Space occupied by chassis in cabinet:	
Basic equipment at transmitting end (for up to 36 measurands)	5 ASA units
Basic equipment at receiving end (for up to 6 measurands)	8 ASA units
Extra tiers for 30 measurands	16 ASA units

(KME)

G. F. Piazza
J. P. Cuendet

The Pulse-Code Remote Control System

621.398:621.38

The new "code" remote-control unit, which in many respects may be regarded as a major achievement, is described in the present article. This equipment is fully transistorized and exhibits a high standard of reliability. In spite of the fact that a number of monitoring actions are first carried out before a command is executed, in an endeavour to completely eliminate faulty manipulations, the command is nevertheless executed within a fraction of a second. The new system offers special advantages in those cases where a large number of commands and indication signals have to be handled, especially when several substations are remote-controlled from a central control point. Such extensive remote-control installations are becoming increasingly popular in the generation and distribution of electricity, as well as for widely ramified industrial installations. The extremely short transmission time is particularly valuable when an "all-round enquiry" has to be made regarding the momentary state of the various elements of a remote-controlled installation.

The Importance of Remote Control

FOR THE OPERATION and supervision of installations engaged in generating and distributing electricity from a central control point, sometimes situated a long way from the station being controlled, a large number of remote-control systems have been developed over the years. Systems in which the connection between the control point and circuit-breakers to be operated was established by through lines, with long transmission links, soon gave way to remote-control systems with selectors and relays, employing elements from the field of telecommunications. Such selector systems operate in a similar way to telephone dialling systems with pulse trains, thus avoiding the principal disadvantages of direct control, namely the large number of connecting lines and the risk of faulty operation due to disturbance effects.

However, selectors and relays, with their moving contacts, are sensitive to dust and chemically aggressive atmospheres. Moreover their operating rate is restricted to about 10–20 actions per second. Consequently they take several seconds to transmit a command or signal. For an "all-round enquiry" for example, where a reply signal is required from every controlled element, the time required becomes of the order of minutes.

The conditions stipulated for remote-control installations are, however, becoming increasingly severe. On account of the growth in the demand for electricity and the importance of absolute continuity in the supply of power, the networks are becoming more complex and more extensive. It is consequently increasingly important for the responsible authorities to be kept closely informed regarding the state of their networks, and for them to be able to intervene rapidly and safely at any of the focal points in a distribution system. Often remote-control systems are combined with direct-acting local systems in the control centres. Therefore the commands imparted by the remote-control system must also be executed instantaneously, without any noticeable delay.

For the remote control of switchgear installations, hydro-electric generating plants and rectifier stations, or for operating extensive conveyor systems, a very high rate of response to commands is normally stipulated, together with minimum need of attention and absolute reliability. The selector systems previously employed can no longer fulfil the strict conditions laid down nowadays.

As part of the development programme for the Brown Boveri electronic system, the elements of the "tele-operation" range (Fig. 1) were employed in the creation of a new remote-control system which,

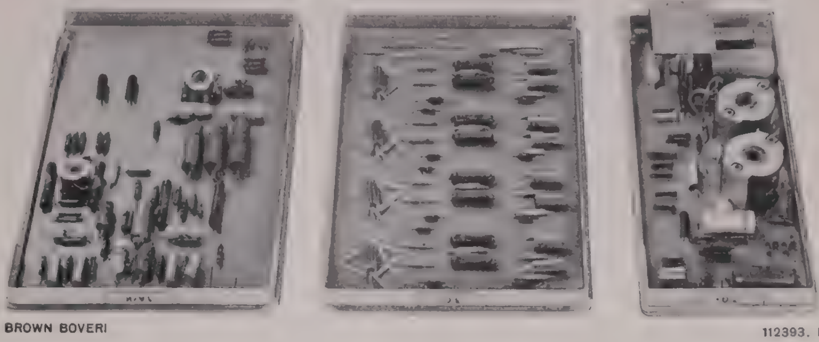

Fig. 1. – Basic elements of the teleoperation range of the Brown Boveri electronic system

From left to right:
Shift register, coding unit, frequency discriminator.

with its transmission speed, freedom from maintenance and facilities for extension, is ideal for employment in all spheres of generation, distribution and utilization of electricity for the remote control of any installation, from the smallest to the largest.

Fundamental Properties

The new remote-control system is a pulse-code system incorporating digital electronic functional units. The circuits function without contacts throughout. Merely for the input and output of commands and reply signals are relays used for connection to the operating and executive elements. The electronic functional units in every case comprise a combination of basic digital circuits, such as counting stages, stores and comparison elements, the principal feature of which is that they operate with a standardized set of pulses.

Owing to the very much greater switching speed of electronic circuits compared with selectors and relays, the time taken to transmit a command has been reduced from several seconds to a mere fraction of a second. The total bandwidth occupied in the a.f. band is small, however, and amounts to not more than 360 c/s.

The extremely high reliability of transmission, which is a characteristic of the Brown Boveri remote-control system, arises out of the following factors:

- The use of a three-point frequency-shift system for extremely reliable transmission of the pulse messages.
- The return of the pulse message to the originating station as a check on the code signal.
- The employment of a pilot code to perform the functions of occupation, execution and acknowledgement.
- The adoption of a principle of repeated attempts at transmission, to overcome the effect of severe interference of brief duration.

The exclusive employment of semiconductors and other high-grade components, together with the compact arrangement of the sub-units, assures a degree of reliability unattainable with equipment employing relays or electron tubes. Comprehensive monitoring systems give a continuous picture of the state of the installation. They simplify the duties of operation by persons who are not specially trained, and ease maintenance, which is already reduced to a minimum.

The employment of a system of "building blocks" with printed circuits and standardized sub-assemblies, tiers and groups of tiers, apart from rationalizing manufacture, simplifying testing and stock-keeping, also provides facilities for extension of an installation on site.

Remote-control installations can be extended in three stages, namely:

- They can start as a small installation for up to 32 double commands (e.g. on-off, open-close, etc.) and reply signals.
- They can be increased to a medium installation for up to 240 double commands and signals.
- Finally, for special duties, they can be extended to handle up to 900 double commands and signals.

Principle of Individual Functional Groups

The introduction of a command or signal into the remote-control system sets off a whole chain of logical actions, which will now be studied in detail.

Input of Information and Coding

The pulse-code remote-control system operates with a fixed pulse rate, given by a central timing element. The timer of the subordinate station is continuously synchronized from the control centre, so that the switching operations in the two stations are controlled by pulses bearing a precisely defined and invariable time relationship with one another. Commands or signals entering from outside must be inserted in this rigid pulse system. It is possible for several commands to occur simultaneously or, on receipt of a command, for the remote-control system to transmit or receive an item of information which arrived earlier. Consequently the commands are keyed in via intermediate relays in a storage chain. The latter consists of storage and coding elements, allocated to the commands or signals, subsequently referred to solely as information. The storage chain is periodically scanned by a check pulse to check its state. If there is no information stored in the chain, the check pulse proceeds from the first store to the last, being newly shaped in each unit. However, if one of the stores in the chain is occupied by information, the check pulse resets this unit, being held up itself and destroyed. On being reset, the particular store emits a pulse at a special output, which is conveyed by 4 wires of a multiple line comprising 8, 12 or 16 wires, according to the extent of the installation, to the holding register. This comprises 8, 12 or 16 bistable circuits, of which 4 are simultaneously triggered by the pulse coming in via the multiple line, i.e. they are in the occupied state, in parallel. Thus the information contained in the store is transferred to the holding register. As soon as the latter is occupied, it closes the gate between the pulse originator and the store (Fig. 2). The check pulses are held up and blocked until the information in the register has been processed and transmitted, whereupon new information may enter the register.

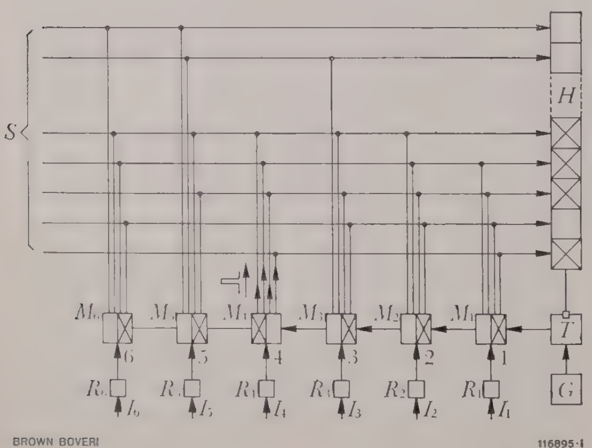

Fig. 2. – Block diagram showing the input and coding of information (command or signal)

I_1—I_6 = Items of information to be handled
R_1—R_6 = Input relays
M_1—M_6 = Stores
S = Multiple line (8, 12 or 16)
H = Holding registers
G = Check pulse transmitter
T = Gate circuit

Store 4 is occupied through input relay R_4. A check pulse coming from the transmitter G through the storage chain scans store 4 and resets it to its initial position. Thus a code signal allocated to I_4 is stored in the holding register via the multiple line.

The commands and signals arrive at the storage chain at arbitrary times, so that there is always a possibility of information arriving at the same time as a check pulse. The introduction of chance information into a rigid pulse system automatically leads to the fundamental problem of coincidence. In this border-line case two pulses of completely different meaning can cancel one another out, which would be equivalent to a loss of information. Despite the high scanning speed, this problem is completely solved in the storage chain. By appropriate choice of the information pulses and check pulses, the former are always given priority, i.e. should the two coincide, it is only possible for the check pulse to vanish but not the information pulse. The transit time of the check pulse is less than 1 microsecond per store.

Owing to this extremely high scanning rate, it was possible, at special request, to design the remote-control system in such a manner that the commands and signals are transmitted according to the order in which they arrive. If their number approaches

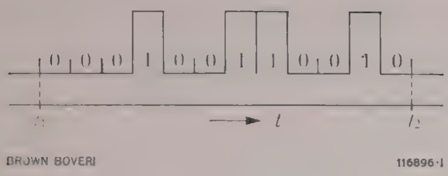

Fig. 3. – The represented period $t_2 - t_1$ contains a code signal with 4 of 12 possible pulses present

t = Time

1000, this still leaves a resolving power of only a few milliseconds; in other words, if two of the thousand commands occur at such an interval, their order of appearance can still be determined. The interval between successive switching operations in power installations, when one action leads to another, amounts to a multiple of this resolving power. It is consequently quite feasible to transmit the desired switching operation in the proper order.

As mentioned above, the "occupation" of each store every time the check pulse passes produces a definite combination of bistable states in the holding register, in that always 4 out of a possible 8, 12 or 16 spaces in the register are occupied. Thus a parallel code is produced, which corresponds unambiguously to the commands or signals keyed into the input units. The number of items of information which can be represented by this code may be calculated with the aid of the binomial coefficient $N = \binom{n}{m}$, where n is the number of available spaces and m the number of spaces occupied at any one time. The diagram in Fig. 3 represents a code with $n = 12$ and $m = 4$.

The number of possible combinations is

$$\binom{12}{4} = \frac{12 \cdot 11 \cdot 10 \cdot 9}{4 \cdot 3 \cdot 2 \cdot 1} = 495$$

The maximum value of the binomial coefficient is given by $m = n/2$, which would yield the best utilization of the code. But it has been proved that the extent of the circuitry only increases slightly with n, since the circuits which process the whole pulse code are the same for all commands. With m, however, the outlay for the circuitry for each command increases linearly with the number of commands. Allowing for the number of commands most frequently stipulated, and having regard to certain requirements, such as the desire for manufacture to be as rational as possible, m was made 4.

Parallel-Series Conversion

The information converted in the input units and now stored in the holding register is characterized by a number of concurrent electrical states. On account of the general shortage of bandwidth common throughout tele-operations, the simultaneous transmission of all states of the holding register is inconvenient. Hence, from the triggered register, a pulse sequence is obtained at a frequency given by the timing element. This process, known as parallel-series conversion, is performed by reading out the register stepwise, not cancelling its content by the scanning, but keeping it stored until the information has been correctly received at the opposite station (Fig. 4). Scanning is performed by a comparison circuit and a shift register. The latter comprises a succession of bistable circuits (toggles), the first of which is triggered by a starting impulse. At the same time stepping pulses are applied to all stages, the effect of which is to restore the momentarily triggered toggle to its initial state, thereby triggering the next. Hence the triggered state is propagated in steps from the first to the last toggle in the shift register, in the rhythm of the stepping pulses. By means of a comparison circuit each stage of the shift register reads out the corresponding stage in the holding register. At the output of the comparison circuit a pulse appears each time a triggered shift register stage encounters a triggered stage in the holding register. Thus the information contained in the holding register is converted into a succession of four pulses at intervals determined by the emptying time of the shift register, their spacing in time corresponding to their relative positions in the holding register. The pulse train so gained is transferred direct to the transmitter, which sends it to the opposite station.

Pilot Code and Transmission

Obviously the information cannot be transmitted without some kind of prior notice to the receiving station. Therefore it is necessary for the start of the

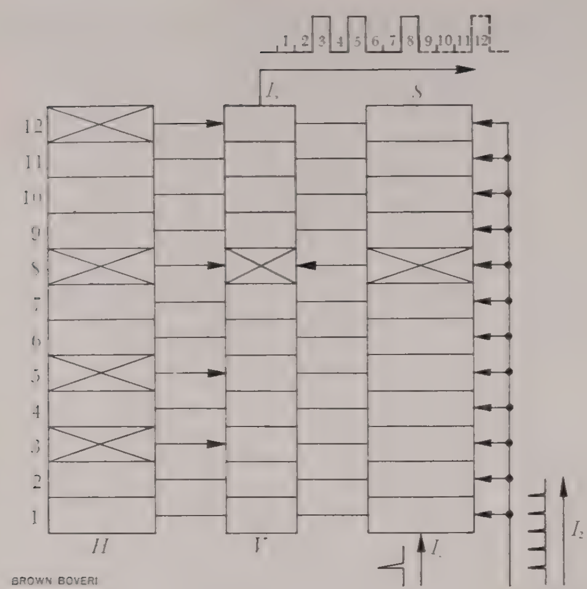

Fig. 4. – Circuit diagram of parallel-series conversion

H = Holding register
V = Comparison circuit
S = Shift register
I_1 = Starting pulse for S
I_2 = Stepping pulse for S
I_3 = Staggered pulse train

The eighth shift register stage, shown in the triggered state, scans the eighth stage of the holding register containing a code pulse and produces the eighth digit of the pulse train at the output of the comparison circuit.

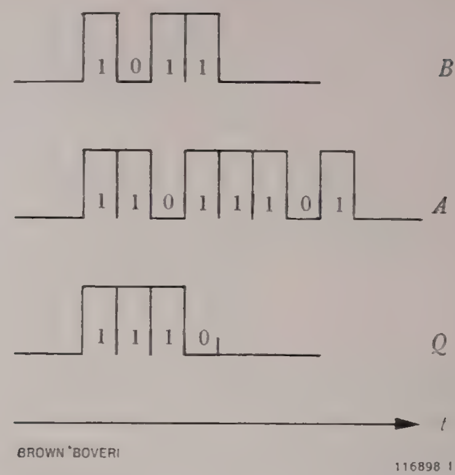

Fig. 5. – Three combinations of the pilot code

B = Occupation
A = Cancellation
Q = Acknowledgement
t = Time

incoming pulse train to be clearly detected and the transmitting part of the receiving station blocked. At the same time the elements receiving the code signal and testing it have to be set in action. This is normally performed by a starting pulse preceding the actual information. But an isolated pulse of this kind can be produced far too easily by disturbances along the route, which might cause the operating elements to function unnecessarily. To overcome this difficulty, the Brown Boveri pulse-code remote-control system employs a pilot code instead of the single starting pulse. This pilot code controls all the auxiliary processes needed for transmission and execution of the various commands and signals. It comprises three of four possible pulses (Fig. 5). The first function of the pilot code is to occupy the opposite station. By extension to a wider choice of code combinations it is possible to control several subordinate stations from a single control centre. To occupy one of the controlled stations, the latter emits a certain code signal (B), which is received by all the out-stations, but which only occupies the one for which the particular pulse combination is intended.

The execution of the commands imparted or the return of the information demanded, after being checked as a safety measure, is effected by a definite combination of the pilot code (A). To rule out the possibility of a disturbance creating the impression of one of the individual combinations and leading to an undesired operation, the executive command is transmitted twice in succession and only carried out when it has twice been received correctly.

The third function of the pilot code is acknowledgement of the executed commands or information (Q). This signal is emitted by the controlled station and releases the installation for the receipt of further information.

The information is transmitted by the system known as three-point frequency shift (Fig. 6). The total bandwidth occupied amounts to up to 360 c/s, depending on the speed of transmission. With this bandwidth a total transmission time of about 300 ms is obtained. The principle of this method is

that the frequency of an oscillator is shifted abruptly (i.e. as pulses) from its steady-state value f_0 to a higher or lower value, $f_0 + \Delta f = f_1$ or $f_0 - \Delta f = f_2$. For transmission of the pilot code the downward shift to f_2 is used, for the coded commands the upward shift to f_1.

Due to the continuous availability of a signal it is possible to superpose a synchronizing criterion, whose task is to keep the timers of the controlled stations in step with that of the control centre. The steady-state frequency allows the transmission link to be continually monitored even when no information is being transmitted.

Series-Parallel Conversion

At the receiving station the incoming pulse message is first stored until the information contained can be passed on. For this the succession of pulses is converted into a series of simultaneous but positionally spaced pulses. This process is the reverse of the parallel-series conversion which took place at the transmitting end, but is likewise performed by a shift register and a holding register (Fig. 7). The incoming pulse train is applied to the comparison circuit. From the pilot code signal preceding the actual information the occupying pulse is obtained which, apart from its other functions, starts the shift register. Since the local stepping pulses and the incoming code pulses are synchronous, it is possible to compare the latter and the individual steps of the shift register. Supposing, for instance, the eighth space of the incoming message contains a pulse, this triggers the eighth toggle of the holding register with the assistance of the eighth stage of the shift register. In this way the succession of pulses in the message is now stored side-by-side in the holding register.

Decoding and Information Output

The next step is to convey an operative pulse to the element for which the information contained in the holding register is intended. For this the holding register controls the potentials of 8, 12 or 16 multiple lines, of which 4—corresponding to the four spaces occupied by the code signal—are conveyed via gates to the transistors which actuate the receiving element concerned. Normally the control transistors

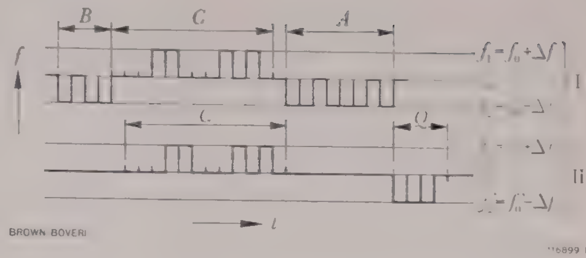

Fig. 6. – Pulse diagram of a complete information transmission

I = Pulse output of transmitting station
II = Pulse train returned from receiving station
B = Occupation
C = Information code signal
A = Executive command
C' = Returned code signal for comparison
Q = Acknowledgement
f'_0, f_0 = Steady-state frequencies for the two transmission systems
Δf = Frequency shift

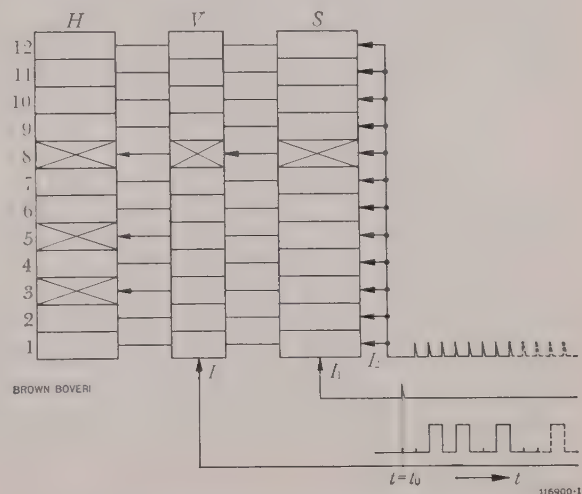

Fig. 7. – Circuit diagram of series-parallel conversion

H = Holding register
V = Comparison circuit
S = Shift register
I_1 = Starting pulse of S
I_2 = Stepping pulse of S
I_3 = Incoming coded information
t = Time
t_0 = End of occupation signal and beginning of coded information

The eighth stage of the shaft register, shown in the triggered state, keys the eighth digit of the coded information signal into the eighth holding register via the comparison circuit.

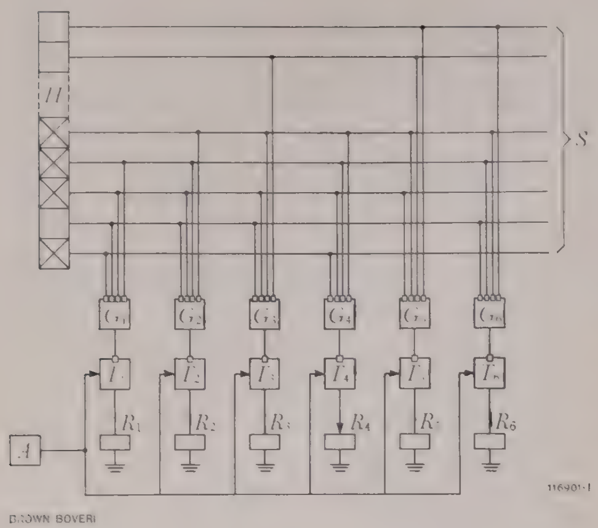

Fig. 8. – Decoding and output of information

H = Holding register
S = Multiple line
G = Gate circuit
T_1—T_6 = Switching transistors
A = Voltage application
R_1—R_6 = Output relays

The voltages conveyed via multiple lines from the holding register to the gate G_4 prepare the transistor T_4, and as soon as the voltage is applied, the relay R_4 operates.

do not carry any current, for safety reasons, and on completion of the checks are briefly made live by the executive command imparted by the pilot code (Fig. 8).

Logic Circuits

This heading covers generally all circuits which are able to handle the information received at their inputs according to definite relations incorporated in the circuit. In point of fact, apart from the actual transmission link, the entire remote-control system is composed of such logic circuits which, on receipt of an item of information, process it until it can be passed on to the opposite station—all completely automatically. In the present chapter, however, only those circuits will be dealt with under this heading which help to assure the extremely high reliability of the operation and transmission of the Brown Boveri remote-control equipment.

The first group of circuits supervise the correct transmission of the code signals. The pulses arriving at the receiving station and belonging to the information message are stored in a holding register, as described above. As soon as the first digit of the information message arrives, the register is read out at the same rhythm as the keying-in process. The pulse train so obtained, displaced by one digit relative to the incoming code signal, is transmitted to the opposite station and checked digit for digit with the code message still stored there in the holding register, to ensure that it agrees.

This check is very effective because it compares the message actually arriving at the receiving station with the coded information stored at the transmitting end, which has not been subjected to any transmission phenomena. The time taken to perform this check is short compared with the duration of a pulse train, because the information sent back for checking is transmitted simultaneously with the original message, except for the brief displacement.

In the receiving station the incoming pulses are counted by a further check circuit. If correctly transmitted, they should always be four in number. This supplementary check on the code eliminates any possibility—and this is already infinitesimal—of faulty transmission, such as might result if a superfluous pulse were to be picked up on the outward journey and lost again on the return trip.

The decoding and output elements connected to the holding register at the receiving end are monitored by a special circuit. Any faults occurring there, which might not be detected by the code check, could lead to faulty operation, even though the code message arrived correctly. At the moment the command is executed, this circuit determines whether only one element has in fact been operated. A fault in the decoding system would be most likely to cause two or more output units to operate simultaneously. In such cases the current applied to the output element would be interrupted in an extremely short time. In such a short time the actuating relay could not possibly move mechanically.

The above checks are not only confined to indicating outwardly that a fault has occurred along the transmission link or in the unit itself, but intervene in the logical course of the transmission of information. If one of these check circuits comes into action, all circuits in the transmitting station are restored to their original position, as far as the holding registers, and the entire transmission process starts again. The repetition does not wait for the whole sequence to be completed but takes place immediately a fault is detected, e.g. if the code comparison proves that one digit does not agree. In the event of a persistent fault the information transmission is automatically repeated seven times, and then an alarm is given. This repeated transmission under adverse conditions appreciably increases the signal-to-noise ratio and thus greatly assists in enhancing the reliability of the Brown Boveri remote-control system, especially when isolated noise peaks occur.

Concluding this chapter, reference may be made to a special logic circuit which ensures that the exchange of information is uniformly distributed in both directions. If a number of commands and signals are stored in both stations, they are transmitted alternately in each direction. A special device prevents one station from keeping the transmission link to itself until it has passed on all the information stored there. This arrangement sometimes proves advantageous. If, for instance, an all-round enquiry is initiated from the control centre round all the subordinate stations, it is still possible to transmit a command to one station while the enquiry is in progress.

Monitoring

In addition to the check circuits described above, the remote-control system contains some more, special monitoring devices. These are mainly concerned with locating functional disturbances which may occur. Due to the incorporation of these special monitoring devices, the installation can be managed and maintained by personnel who have not had any special training.

The first group of these circuits include the following facilities:

- Alarm given when a fuse blows;
- The channel supervision system, which picks up in one of the two receivers when the a.f. signal fails;
- Supervision of the chain sequence; this keeps a continuous check on the state of the storage chain;
- Checking the seven-fold repetition of an attempt to transmit the signal.

A second monitoring group includes visual indicators which provide information regarding the state of important parts of the installation. On a printed test circuit which can be plugged into each chassis at a point specially provided, it is possible to carry out a visual check of up to 20 switching functions.

Power Supply

The remote-control system operates at a voltage of 24 V d.c. The consumption depends on the extent of the installation and amounts to about 2·5 A for the basic unit. A group of tiers for 20 double commands and signals consumes about 1·5 A. This relatively high consumption, for semiconductor units, is due to the high transverse currents needed to ensure reliable operation by the bistable circuits.

To feed a station for 100 double commands and signals, a power pack is provided, which may be employed as an independent, magnetically regulated mains rectifier with filtered 24-V output, or as charging set for a relatively small 24-V battery. Operation with a buffer battery is recommended because, in the event of mains failure, the full capacity and reliability of the remote-control unit is assured, without the least interruption.

Mechanical Design

By employing the "building block" principle, the design is kept compact, yet clearly defined. The

Fig. 9. – Control unit of a remote-control installation

Some of the tiers are shown with the front plate removed, to give a better view of the method of mounting the printed circuits.

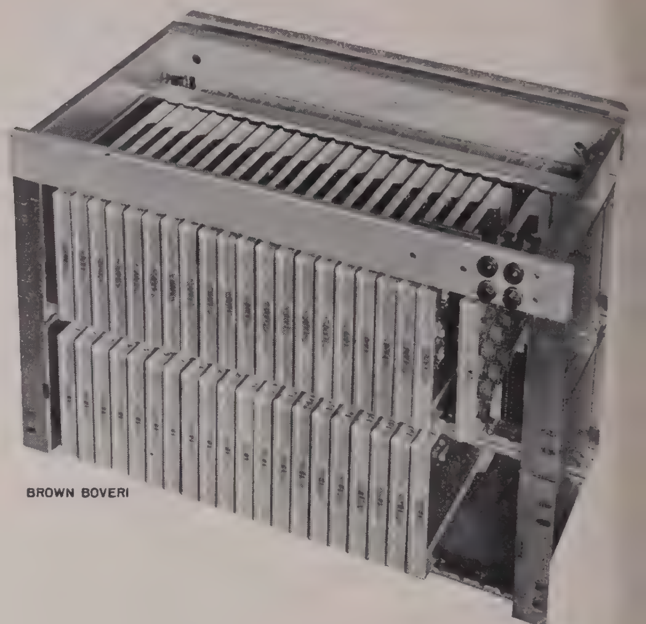

Fig. 10. – Group of tiers for 20 double commands and indication signals

The input and output relays are mounted on a hinged plate. The cable trunking can be seen at the top and on the right.

printed circuits, sub-assemblies and tiers employed were fully described in the article beginning on page 670 of this issue.

A remote-control unit is mounted on a hinged frame in a standardized sheet-metal cabinet (Fig. 9). Here a distinction must be made between the basic unit which, regardless of the number of commands or signals, occupies a height of eleven ASA divisions. In a further group of tiers with a height of seven ASA divisions, the equipment for a further 20 commands and signals can be accommodated. For still further extension of the installation, the equipment can be increased by adding seven divisions for every twenty signals, until the final number is attained. With this rational layout, the wiring can be laid neatly and accessibly. By using vertical and horizontal cable trunking made of plastic the former unwieldy cable harnesses are avoided altogether.

(KME)

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THE ELECTRONIC DIGITAL SYSTEM CONTROLLER

621.316.728:621.311.161

The digital system controller is a very accurate controller having a proportional-integral action, which can be employed for a variety of tasks in modern interconnected power systems. Its design is based on the exclusive use of units from the digital range of the Brown Boveri electronic system, and it functions according to much the same principles as digital computers.

Commencing with the control equation and the conditions stipulated regarding accuracy, the present article describes the functions of the controller, followed by an explanation of the equipment for the dosage of the correcting condition and conveying it to the turbine governors.

THE ADVANTAGES of interconnected operation of power plants supplying electricity leads to an extension of parallel operation by an increasing number of systems. This heightens the importance of system control, which is responsible for the maintenance of the frequency and the agreed transfer of power between the collaborating power companies. The fundamentals and problems of power system control have already been amply dealt with in numerous publications [1]. The present article will therefore only go into them as far as they concern the development of the Brown Boveri digital controller.

Fundamental Principles

The Control Equation

The digital system controller has a proportional-integral (PI) action. To account for this, it is pointed out that a control circuit always requires an integrating element if the variable to be controlled has to be restored to a definite desired value after every deviation. The proportional effect allows a much higher control speed to be attained than would be feasible with a pure integral controller [1].[1] The output correcting condition Y is formed in the controller as the sum of a proportional and an integral fraction, as given by the following equation applying to load-frequency control:

$$Y = C_P(\Delta P + K \cdot \Delta f) + C_I \int_0^t (\Delta P + K \cdot \Delta f) \cdot \mathrm{d}t$$

in which

Y = correcting condition (output signal of the system controller) in %[2]

ΔP = deviation in tie-line power (difference between desired and momentary value) in MW

Δf = deviation in system frequency in c/s

K = system bias of the controller in MW per c/s (it determines the extent of "frequency aid")

C_P = proportional constant in % per MW[2]

C_I = integral constant (see below)

$T_n = C_P / C_I$ = integral action time in s[3]

Since it is preferable in service to employ the value T_n as setting, instead of the integral constant C_I, it can be substituted in the equation, as follows:

$$Y = C_P \cdot \left[(\Delta P + K \cdot \Delta f) + \frac{1}{T_n}\int_0^t (\Delta P + K \cdot \Delta f) \cdot \mathrm{d}t\right]$$

The equation for pure load control is:

$$Y = C_P \cdot \left[\Delta P + \frac{1}{T_n}\int_0^t \Delta P \cdot \mathrm{d}t\right]$$

For pure frequency control an analogous equation applies.

[1] The figures in brackets refer to the bibliography on p. 749.

[2] The meaning of these units is explained on page 749.

[3] T_n is defined as follows: The integral action time is that period which elapses, with constant deviation of the controlled variable, until the correcting condition has changed under the integral influence by the same amount as produced by the proportional influence alone.

Stipulations Regarding Accuracy

It must be possible to employ the digital controller under a wide variety of system conditions, e.g. as load-frequency controller, load controller or frequency controller, alone or in conjunction with other system controllers, in weak or powerful systems. These conditions are described in detail in the article [1]. In large interconnected systems with a high bias K, only a small deviation in the frequency may represent an appreciable deviation in the tie-line power. According to the recommendations of the Union pour la Coordination de la Production et du Transport de l'Electricité (UCPTE), in a system having a bias of 2000 MW per c/s and telemetering range for a tie-line power of 200 MW, the accuracy of *frequency measurement* should be $\pm$ 0·002 c/s.

If, in an independent large system, the frequency is controlled by two or more system controllers, installed in different power stations (pure frequency control), not only must the frequency be measured with great precision, but the integration of the deviation Δf must be performed with the utmost accuracy, to prevent "divergence" between the various controllers and the resultant load shift between the power stations.

Corresponding conditions also apply to the *measurement of power* with decentralized system controllers [1] with load control or load-frequency control. In these cases the measurement of the tie-line power as such does not have to be very accurate, but the evaluation of the telemetered signal in the decentralized system controller must. By employing the Brown Boveri frequency-variation telemetering system, as will be explained later, it is also possible to satisfy this stipulation, provided the power inputs of all system controllers are fed with the output frequency of the same telemetering transmitter.

The Digital Principle

In a device designed on the analogue principle, the main quantities are represented, for instance, as current, voltage, torque, etc. The precision and constancy of the components utilized largely determine the attainable accuracy.

In a digital device the items of information exist in the form of pulse trains or codes representing numbers, the codes being generally constituted of only two digits, L and 0. These two digits are represented in electrical circuits, for example, by the states "On" and "Off". As long as these two states can be clearly distinguished, the data of the components, and changes in them due to temperature, ageing, etc., have no influence on the accuracy, which can therefore be increased almost without restriction.

In view of this high sustained accuracy, the digital principle was adopted for the new electronic system controller.

The basic elements of the controller are a number of fundamental circuits, such as

Schmitt triggers, for generating impulses,
Bistable circuits, for counting and storage,
Gates, for blocking or passing impulses.

All these circuits employ transistors and semiconductor diodes. They have to satisfy very severe conditions since the maximum counting frequency is 750 kc/s and the shortest impulse lasts 0·3 μs. Further information regarding the fundamental circuits and principles of digital devices is contained in article [2].

Description of the Digital Controller

The layout of the system controller may be gathered from the block diagram in Fig. 1. The manner in which it functions will now be briefly described, with reference to this diagram.

Measurement of Frequency Deviation Δf

A frequency can be measured by producing one pulse every cycle and counting the number of pulses during a definite period. For example, if the mains frequency is counted in this way over a period of 1 second, a total of 50 pulses are counted. The measurement is therefore only accurate to $\pm$ 1 c/s.

To attain the desired accuracy of measurement the mains frequency is multiplied by the factor 10^4 in a multi-stage multiplier, i.e. from 50 c/s to 500 kc/s. The period over which it is counted, which will be called the "count-in interval", was made 0·1 s.

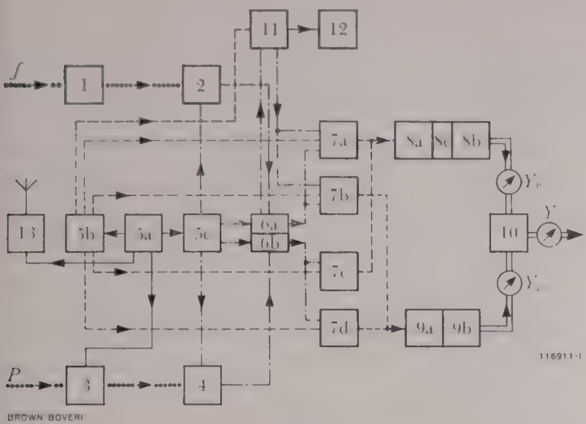

Fig. 1. – Block diagram of the digital system controller responsible for control of the frequency and transfer of power between interconnected systems

1 = Multiplier for the system frequency
2 = Desired-value register for system frequency
3 = Frequency converter and multiplier for the telemetering frequency for tie-line power
4 = Desired-value register for power
5a = 100-kc/s frequency standard
5b = Counting frequencies
5c = Time-base
6a = Pulse evaluation for frequency
6b = Pulse evaluation for power
7 = Pre-registers
a = Proportional for frequency
b = Integral for frequency
c = Proportional for power
d = Integral for power
8a = Proportional register
8b = Digital-to-analogue converter
8c = Holding register
9a = Integral register
9b = Digital-to-analogue converter
10 = Output amplifier
11 = Δf register
12 = Δf indicator
13 = Monitoring receiver
f = System frequency
P = Tie-line power (as telemetering frequency)
Y = Correcting condition (controller output)
Y_P = Proportional fraction of Y
Y_I = Integral fraction of Y
.... = Controlled variables
---------- = Counting pulses for the registers
-·-·-·-·- = Start, reset, time-reference and end pulses
═════ = Correcting condition as direct current

This time is therefore small compared with the other time constants of the control circuit. Within the count-in interval about 50000 pulses are counted; the resolving power of $\pm$ 1 pulse therefore corresponds to $\pm$ 0·001 c/s.

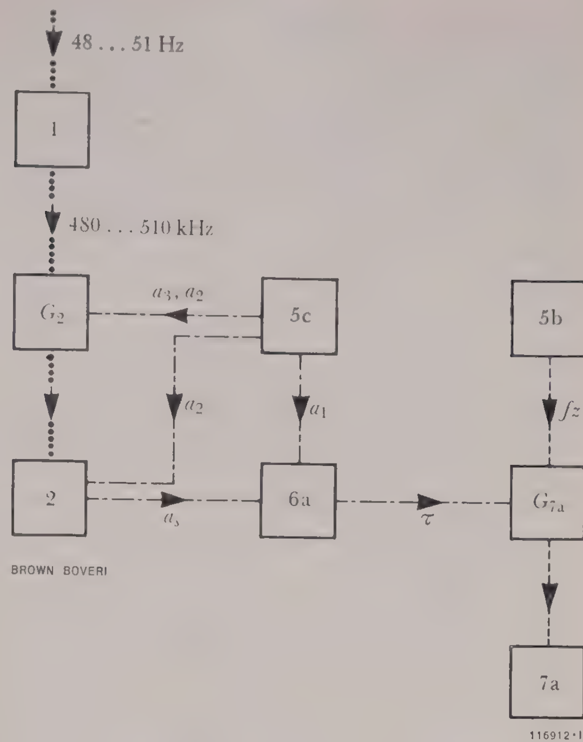

Fig. 2. – Simplified diagram to illustrate the measurement of the frequency deviation Δf

G_2 = Start gate for desired-value register
G_{7a} = Gate at input to pre-register
a_1 = Time-reference pulse
a_2 = Reset pulse
a_3 = Start pulse
a_s = End pulse when desired-value register is full
f_z = Counting frequency
τ = Time between time-reference and end pulses

Other notation as in Fig. 1.

The pulses emitted by the frequency multiplier are counted into the desired-value register composed of bistable circuits. The term register generally implies a pulse store. The desired-value register has the special property of variable storage capacity, enabling the frequency value to be adjusted. If the number of spaces in the register is 50000, corresponding to a desired frequency of 50 c/s, and if the frequency to be measured is exactly 50 c/s, it takes precisely 100 ms to fill the register completely. At higher mains frequencies the task of counting-in obviously takes less time, and at lower frequencies longer than 100 ms. The difference τ between the time actually needed for counting in and the "reference time" of 100 ms is a measure of the frequency deviation Δf. It is now easy to understand why

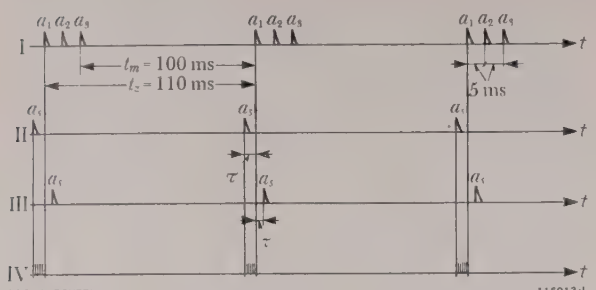

Fig. 3. – Pulse diagram for the measurement of the deviation Δf

I = Pulses generated by the timer (For notation see caption for Fig. 2)
II = End pulses of the desired-value register when the momentary value of frequency is greater than the desired value. Δf is positive
III = End pulses of the desired-value register when Δf is negative.
IV = Counting-frequency pulses counted into the preregister during the time τ when Δf is positive
τ = Time elapsing between end pulse and time-reference pulse
t = Time scale
t_m = Duration of measurement, count-in time
t_z = Duration of a measuring sequence

changing the storage capacity alters the desired value. If, for instance, the number of spaces is reduced to 49800, the "reference time" of 100 ms is reached at a frequency of 49·8 c/s. To determine Δf the time τ has to be measured (Fig. 2 and 3).

Counting begins at the instant the starting pulse a_3 from the time base opens the start gate. Exactly 100 ms later the time-base emits the time-reference pulse a_1. As soon as the desired-value register is full it produces the end pulse a_s. The time τ, which corresponds to the deviation Δf, is then the difference in time between the pulses a_1 and a_s. The sign of Δf is determined by the order in which the two pulses occur.

Following the count-in time of 100 ms is the evaluation time of 10 ms, in which the time τ is processed, the start gate being closed by the pulse a_2 and the register reset to zero. The entire measuring sequence thus lasts 110 ms. The measurement is continuously repeated, hence the frequency deviation is measured 9 times per second. The means of measuring the time accurately will be referred to later.

Measurement of Power Deviation ΔP

The momentary value of the tie-line power is introduced into the system controller as frequency by the frequency-variation telemetering system. For this there are two telemetering frequency bands available, which can be transmitted by the carrier links as channels superposed on speech.

The telemetering frequency is converted and multiplied, bringing it roughly into the same range as the multiplied mains frequency, and is measured in the same manner as the latter. Direct processing and very accurate measurement of the telemetering frequency assures fulfilment of the stipulations regarding the coordination of two or more system controllers, referred to in the chapter on accuracy requirements.

The measurement sequence for ΔP is displaced by 10 ms relative to that for Δf, because the subsequent registers cannot handle two pulse trains simultaneously.

Pulse Evaluation and Pre-Registers

The pulses a_1 and a_s pass to the evaluation stage, where the sign of Δf is determined. From the evaluation stage the gates are opened to the input of the pre-registers for the frequency during an interval of τ, so that a number of pulses proportional to Δf are counted simultaneously into the proportional and integral pre-registers. Subsequently the same process is repeated for ΔP.

The two *constants*, system bias K and the telemetering range for the tie-line power are introduced in the pre-registers. The manner in which this is done will be demonstrated, taking K as an example. Dividing the pulses counted in for Δf in the ratio 2:1 corresponds to the multiplication $^1/_2\,\Delta f$. If the relative value 1 is substituted for the maximum value of K, we obtain the relative values 1, $^1/_2$, $^1/_4$, $^1/_8$... for successive series connection of pulse dividers (ratio 2:1). To achieve finer graduation, two counting frequencies in the ratio 1:1·5 are employed for counting into the pre-registers, e.g. 333 kc/s and 500 kc/s. By alternate employment of these frequencies, and the insertion of pulse dividers, we ultimately obtain the series of constants

$$1,\ \frac{1}{1{\cdot}5},\ \frac{1}{2},\ \frac{1}{1{\cdot}5\times 2},\ \frac{1}{4},\ \frac{1}{1{\cdot}5\times 4},\ \frac{1}{8},\ \text{etc.}$$

Hence the constant is not continuously adjustable. The graduation obtained by this method is, however, sufficiently fine for practical requirements on the one hand and, on the other, permits adjustment over a wide range without any loss of accuracy.

The pre-registers consist of a chain of bistable circuits [2], which are switched in or out according to the set constant, each of them acting as a pulse divider with the ratio 2:1.

Proportional and Integral Registers, Digital-to-Analogue Converter and Output Amplifier

The pre-registers pass on the pulses to the proportional and integral registers, which also consist of bistable circuits. The constants C_P and T_n are taken into account here by the same principle as described for K. (It may be pointed out additionally that, for the introduction of all constants, which are dependent upon one another to a certain extent, a total of 6 and not 2 counting frequencies are required.) Since the deviation in the controlled variable may be positive or negative, the registers are arranged for counting forwards or backwards. Changing over the bistable circuits to addition or subtraction is performed by the pulse evaluation stage.

At the end of each measuring sequence of 110 ms the proportional register is reset so that counting can start all over again; at the same time its content, which corresponds to the term $C_P\ (\Delta P + K\,\Delta f)$, is transferred to a holding register. The latter stores the result of the calculation for one full sequence. In the subsequent digital-to-analogue converter, by addition of the currents graduated in the ratio 1:2:4:8 ..., the proportional fraction Y_P of the output variable is produced in the form of a direct current across a common resistance. It is inherent in the nature of this conversion that the output correcting condition does not vary continuously, but in small steps, which are insignificant for practical operation.

The integral register is not reset; it can be returned to zero though at any time by pressing the reset button. The occupation of the register is converted to the integral fraction Y_I of the output correction in the subsequent digital-to-analogue converter. Y_P and Y_I are both indicated by instruments, then added and amplified in the d.c. output amplifier. The process of integration performed by summation in a register has the particular advantage that the zero remains absolutely stable and even the smallest deviations can be handled with accuracy and instantaneously.

Δf Register and Indication

For load-frequency control it is desirable to be able to limit the *influence of the frequency*, in order that, in the event of a serious breakdown in an adjacent system causing a severe drop in frequency, overloading is avoided in the controller's own system. The frequency deviation Δf_L, up to which the controller should function normally, is set by means of a stepping switch controlling the Δf register. If the measured deviation Δf exceeds the limiting value Δf_L, only the latter deviation is effective in the controller for formation of the correcting condition. The frequency deviation Δf is indicated on the control desk with four digits, e.g. + 0·132 c/s, by means of glow-type numerical display units.

Frequency Standard, Time-Base, Counting Frequencies and Monitoring Receiver

It has already been pointed out that digital measurement is based on measurement of time, upon the precision of which the accuracy of measurement depends. The frequency standard is a 100 kc/s magnetostriction oscillator, whose accuracy and stability are of the order of 10^{-7}. By multiplication and division of the frequency, the counting frequencies are obtained from the 100 kc/s, and the start, time-reference and reset pulses produced in the timer.

To check the frequency standard, and for retuning the oscillator, should the need arise, the controller contains a receiver tuned to the Droitwich 200-kc/s transmitter, with a means for comparing the frequencies [3]. Magnetostrictive filters enhance the selectivity of the receiver.

Power Pack

The system controller, with the exception of the frequency comparator in the monitoring receiver

and the Δf indicator, is supplied from a 48-V battery. Conversion to the lower internal supply voltages is performed by a d.c. converter equipped with transistors. The voltage for the digital-to-analogue converter is supplied by a high-grade stabilizer.

Monitoring Devices

Apart from the careful dimensioning and manufacture of the unit, monitoring devices and interlocks provided to prevent faulty handling are primarily responsible for the reliability. A special test chassis and other devices allow the functions of the unit to be tested.

The following examples of monitoring devices may be quoted:

In the absence of any input value (frequency or tie-line power) the system controller automatically blocks and emits a constant correcting condition.

In the event of an internal breakdown, the appropriate supervisory element gives an alarm and carries out the changeover switching actions needed to prevent false control.

To facilitate operation, visual and optical signals are given as soon as the integral fraction of the correcting condition approaches the upper or lower end value.

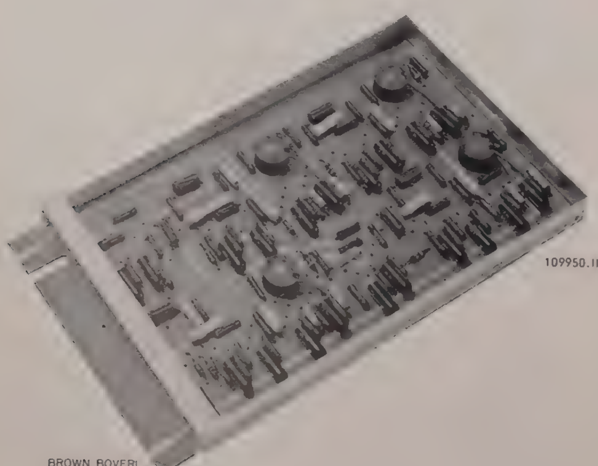

Fig. 4. – Plug-in functional unit on printed circuit

On this plate, measuring 110 × 200 mm, are 21 transistors, 11 crystal diodes, 10 coils and transformers, 19 capacitors and 65 resistors.

Design of the Digital System Controller

The unit is fully transistorized. The lower power consumption of the circuits containing transistors

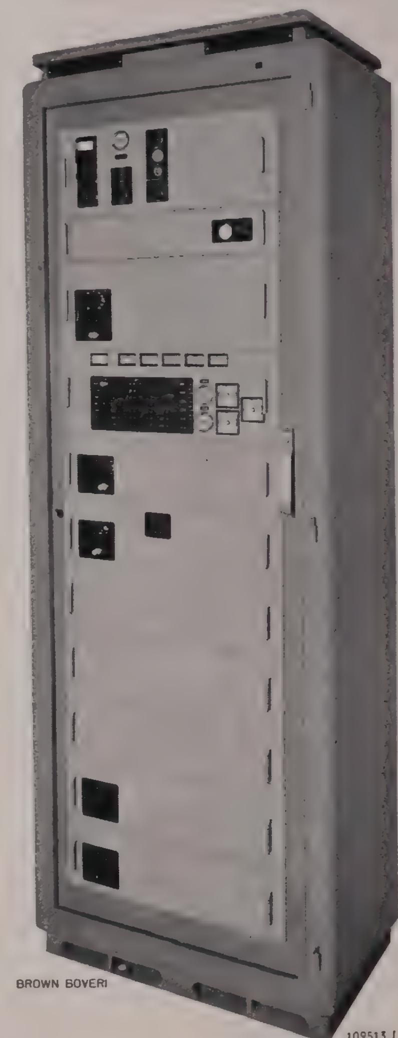

Fig. 5. – Digital system controller

From top to bottom the cabinet contains the following chassis:

Power pack and output amplifier,
Monitoring receiver,
Standard frequency, time-base, counting frequencies
Test chassis,
Desired-value registers,
Pulse evaluation stage,
Pre-registers,
Proportional register,
Integral register,
Multiplier for mains frequency,
Multiplier for telemetering frequency giving tie-line power.

Fig. 6. – Digital system controller

The hinged frame, when swung out, shows the chassis with the compact functional units constructed of printed circuits. This cabinet contains a total of about 1000 transistors and 1100 semiconductor diodes.

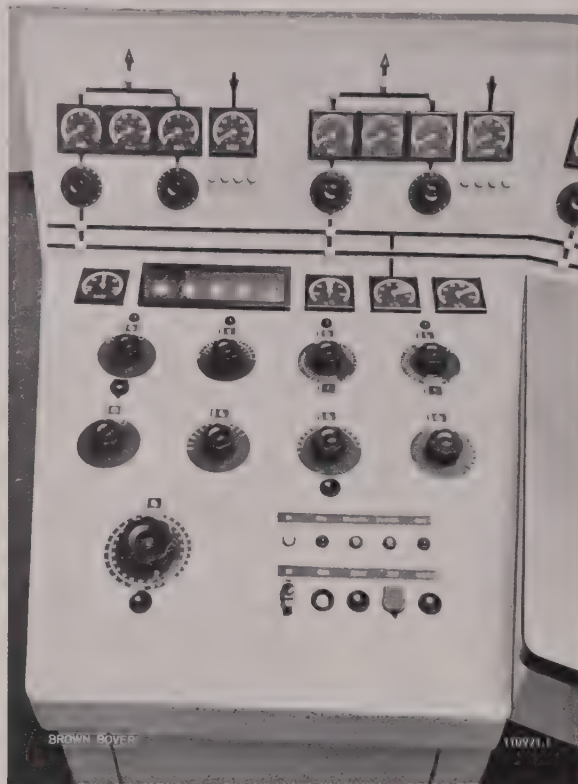

Fig. 7. – Control desk of the digital system controller from which the power exchange between Switzerland and neighbouring countries is controlled

All controller constants and desired values are set by means of rotary knobs, which actuate multi-stage switches. The dials are calibrated. In the upper part of the desk can be seen two of the six outputs for dosage of the correcting condition and transmitting it to the controlling power stations.

facilitates compact construction, using plug-in printed circuits (Fig. 4). The cabinet in which the controller is mounted is illustrated in Fig. 5 and 6. A separate cabinet contains the power pack and the code converters for the Δf indication. It has enough space for additional elements, e.g. for dosage and distribution of the correcting condition.

The operating and indication elements are housed in a desk to suit the installation. Fig. 7 shows a typical example from a completed installation. All controller constants and desired values are set by means of stepping switches.

The Digital System Controller in Practice

Some of the problems associated with the employment of the digital system controller in practice will now be discussed. If the system being controlled is joined to the adjacent systems by a number of tie-lines, the sum of all tie-line powers must be produced and conveyed to the controller as a telemetered input. How this can be done may be explained with reference to Switzerland.

The most important load dispatching centres contain automatic control distributors [4], or these are in the course of erection, by means of which any telemetered or locally measured power values can be totalled. Brown Boveri frequency-variation telemetering links connect the control distributors with

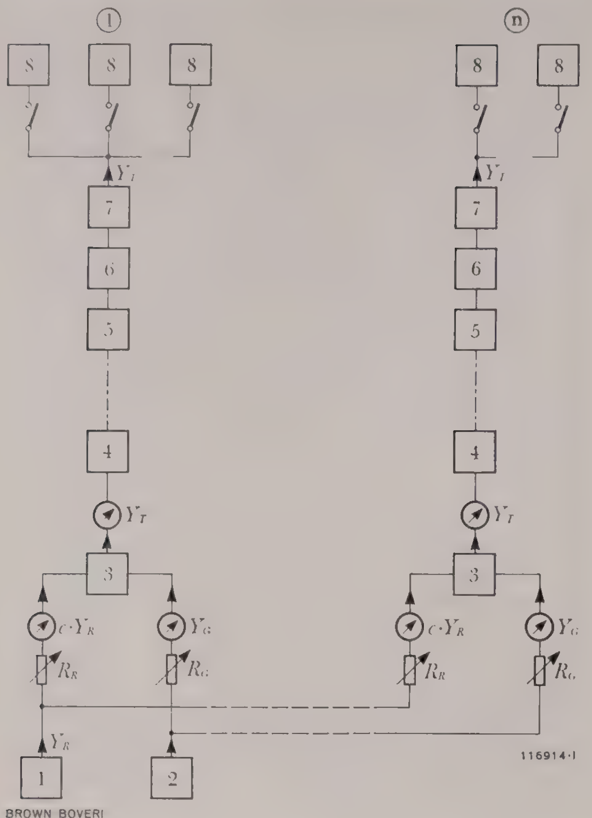

Fig. 8. – Schematic diagram showing the dosage and transmission of the correcting conditions to the controlled generating stations

Only two of the many possible output lines are indicated.

1) = Generating station 1
n) = Generating station *n*
1 = Digital system controller
2 = Stabilized d.c. voltage
3 = Summation and transfer switchgear
4 = Telemetering transmitter
5 = Telemetering receiver
6 = D.C. amplifier
7 = Follow-up control
8 = Turbine governor
R_R = Potentiometer for dosage of correction Y_R by adjusting factor *c*
R_G = Potentiometer for setting a correction for base load Y_G
Y_R = Correction at system controller output
Y_G = Correction for base load
Y_T = Correction communicated to turbine governor

one another, as well as the points at which the tie-line powers are measured, and the controlled power stations. On account of its small time constant this telemetering system is ideal for control purposes. The telemetering channels can be utilized for transmission of power values or corrections.

If several generating stations are controlled from one system controller, their dynamic responses must be matched to a certain extent. The manner in which this problem is tackled is explained in the article beginning on page 750.

Processing the Correcting Condition Emitted by the System Controller

The correcting condition Y_R from the system controller varies in the range 0–100%. The turbine governors of the machines concerned with control are so arranged that, at rated frequency, they are switched to no-load speed by the application of a correction of $Y_T = 0\%$ to the governor input, or to full-load speed by the application of $Y_T = 100\%$. This is known as primary control.

Having regard to the operating conditions, it must be possible for the share of each power station concerned with control to be set individually. This is performed by a *dosage unit,* preferably mounted on the same control desk as the operating elements for the controller, with a different number of outgoing lines, according to the particular installation. Each outgoing line contains a potentiometer R_R for dosage (weakening) of Y_R, and a further potentiometer R_G for setting the base-load correction Y_G, together with the necessary instruments and transfer switches (Fig. 8).

In the general case

$$Y_T = c\ Y_R + Y_G$$

The factor *c* can be set in the range 0–1 by means of the potentiometer R_R.

The correction Y_T is conveyed to the controlled power stations direct or over telemetering links. Since the machines in these stations are connected up according to demand, Y_T is not an absolute measure of the power output of the particular station, but for the opening of the turbines.

With telemetering links a system of follow-up control is incorporated in the station as a safety precaution. In principle this consists of a potentiometer whose output voltage is continuously controlled to match the incoming correcting condition. If a defect occurs in the telemetering system the turbine governors are immediately disconnected from the d.c. amplifier following the telemetering receiver, and

switched over to the potentiometer, which now emits a constant voltage and thus keeps the output of the machine at the value ordered by the controller before the fault occurred.

Selection of Constants T_n and C_P

The integral action time T_n is usually set roughly to a value corresponding to the time constant of the main servomotor of the turbine governor. The setting of the proportional constant C_P may be explained by considering the example of pure power control. The total increase in output of all controlling machines, resulting from an increase from 0 to 100% in the correction Y_R of the system controller, is referred to as the available controlling power P_R.

$$P_R = c_1 P_1 + c_2 P_2 \ldots + c_n P_n$$

where c_n is the factor set on the dosage potentiometer R_R of the n-th generating station

P_n is the sum of the outputs of the machines concerned with control in the n-th generating station

Supposing the correction is 70%, this means that the momentary output of the controlling machines is 70% of the available controlling power (ignoring the not quite linear relationship between the correction Y_T and actual machine output).

Taking into account the conditions in the power system, and particularly the hydraulic properties of the generating stations, it is necessary to stipulate how large the change in the output of the machines ΔP_R due to the proportional effect has to be if the tie-line power is to change by ΔP_i. If, for instance, this ratio is made $\Delta P_R/\Delta P_i = 0{\cdot}5$, and P_R is 200 MW, the constant to be set on the controller is

$$C_P = \frac{\Delta P_R}{\Delta P_i} \cdot \frac{100}{P_R} = 0{\cdot}5\,\frac{100}{200} = \begin{cases} 0{\cdot}25\% \text{ per MW} \\ \text{of tie-line power} \end{cases}$$

Hence C_P denotes the change in output of the machines caused by a change of 1 MW in the tie-line power, expressed as a percentage of the available controlling power.

Operational Experience

The first Brown Boveri digital system controller has been in service in the Lavorgo power station of the Aare-Tessin Electricity Co. since June 1959. A second is operating in the generating station of the Elektrizitätsgesellschaft Laufenburg in Switzerland. Since March 1960 it has been used to control the transfer of power between the Swiss system and an adjoining network. Both controllers are performing their task with great success. The station staff have quickly become accustomed to their operation. The ease with which the constants are set and the ability to respond to changing operating conditions without loss of time are features which have gained special appreciation.

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MATCHING THE DYNAMIC CHARACTERISTICS OF TURBINES TO THE REQUIREMENTS OF SYSTEM CONTROL

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The present article examines the dynamic response of different kinds of primary controllers for water turbines and states the conditions for mutually balancing the response of the various types of controllers actuated by a common correcting condition, and the circuit elements required to make parallel operation possible. In conclusion, a transistorized dynamic correction amplifier will be described; this unit has been in regular service for some time and allows a number of generating stations to be controlled from a single system controller.

IF, IN A network distributing electrical energy, a number of generating stations whose turbine sets are equipped with primary control are controlled from a central point so as to produce a fixed tie-line power, difficulties may be experienced if the controlling elements have different dynamic characteristics. These become apparent as oscillation of the load between the individual generating stations.

Now if a controlled system comprises several controlled objects, for which there is a common correcting condition as well as a common controlled variable, the stipulation regarding adequate stability at a suitable rate of control is augmented by the demand for a definite load distribution between the parallel controlled objects. In the steady state the distribution of the load is determined by the dosage of the correcting condition to the corresponding controlled objects, provided they have linear static characteristics, this being assumed in subsequent considerations.

During the actual control process the load distribution is largely dependent upon the dynamic response of the individual controlled objects. If there is considerable diversity in their transfer functions, the dynamic load distribution will differ appreciably from the steady-state distribution. Consequently the load may be expected to oscillate between the individual controlled objects, resulting in undue wear and tear on the control elements. These shortcomings can only be eliminated by mutual adaptation of the dynamic characteristics of the different controlled objects, for which one of two methods may be adopted:

- making changes in the controlled objects,
- inserting dynamic matching elements in the circuits of the controlled objects.

The following remarks dealing with dynamic matching will be confined to a few examples from the sphere of power system control, because a general discussion of this problem would greatly exceed the scope of the present article.

Specified Conditions

In power system control it is frequently stipulated that a number of parallel generating stations have to be regulated to produce a definite tie-line power, either because the controlling power of a single station is inadequate, or because the power company expresses certain desires, such as improving the hydraulic efficiency, or prevention of undue fluctuation in the pressure so as to save wear and tear on the elements adjusting the output of the turbines.

If only one power station with a number of identical machine sets is made responsible for control, it is generally a simple matter to select the constants of the system controller to ensure that the rate of control satisfies the requirements and to keep the strain on the governing elements in tolerable limits. It is quite a different matter though, when various types of turbines have to be controlled from a central system controller. Here difficulties may be anticipated if there are marked differences in the overall response of those parts of the control circuit which are situated between the controller output and the nozzle or guide vanes of the controlling machines. If a relatively slow rate of control is not employed, the elements of the governing gear of individual turbines may be subjected to inadmissibly severe

stresses, resulting in the load oscillating between machines in the extreme case.

In the case of hydro-electric plants with Pelton and Francis turbines, which are commonly employed for system control, the difference in response with primary control is due to two factors:

- different systems of turbine control, such as regulators with an acceleration influence, or with temporary offset;
- widely different hydraulic performance, resulting in different time constants of the combinations of main servo-motor and governor for the various turbines.

The means by which the dynamic responses of different turbines can be matched will be described later. They meet the requirements of many power undertakings, namely that as regards system frequency there should be no interference with the original control properties.

Fundamental Theory

The different response of individual turbine control systems is mainly due to the differences in the designs of the combination of governor and main servo-motor. Therefore the point from which the present investigation will start is the derivation of the transfer functions of the two alternative systems, i.e. the controller with acceleration influence, and the controller with temporary offset. These functions will be derived from the functional circuit diagrams of the main parts of the installation. The object of subsequent considerations will therefore be to explain

- how the time constant of a control system with acceleration influence can be converted into a preset value, and
- how the transfer function of a system with temporary offset can be converted into that of a system with acceleration influence.

Turbine Control

The transfer functions will only be established with respect to the relative opening of the nozzle or guide vanes of the turbine, neglecting the pressure surge and the inertia of the generator, and assuming more or less complete linearity, and expression in terms of the relative output of the machines.

Symbols

$p = \dfrac{P_M}{P_{M\,max}}$ = relative machine output

Δf = deviation of system frequency from desired value

y = relative correction of system controller

δ = permanent offset

$\dfrac{1}{\delta_b}$ = initial influence of accelerometer

δ_v = temporary offset

T_H = time constant of the main servo-motor with closed control circuit, without acceleration influence or temporary offset

T_b = time constant of the accelerometer

T_v = time constant of the temporary offset

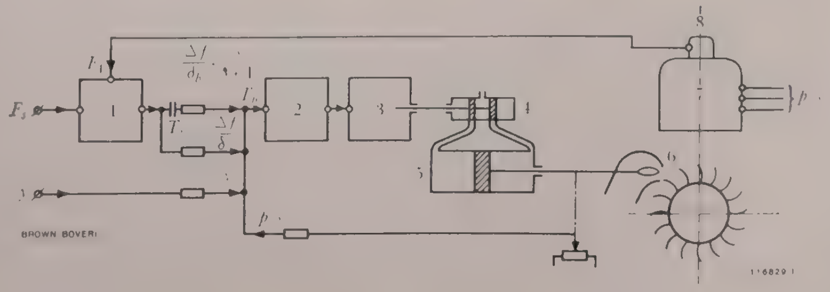
s = differential operator

Controller with acceleration influence

A characteristic feature of this system is that, in addition to the deviation of the system frequency from its desired value, it also utilizes the approximate derivative of the frequency as correcting condition in the turbine governor. The overall correction acts on the main servo-motor via amplifiers, the position of the servo-motor being fed back to the controller. Fig. 1 shows the arrangement of the control circuit,

Fig. 1. – Circuit of the controller with acceleration influence

1 = System measuring frequency
2 = Amplifier
3 = Electro-mechanical transducer
4 = Control valve
5 = Main servo-motor
6 = Nozzle of a Pelton turbine
7 = Generator
8 = Permanent-magnet generator



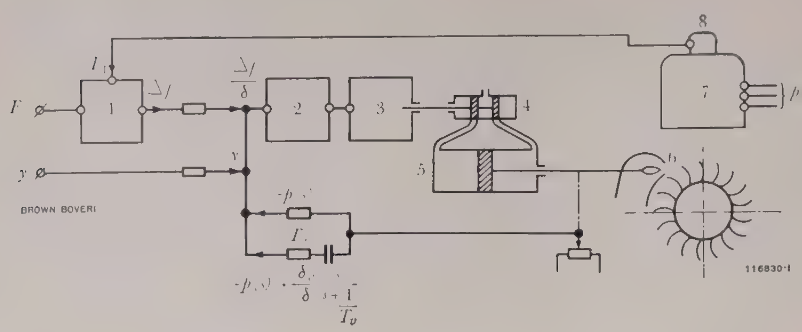


Fig. 2. – Circuit of a controller with temporary offset

1 = System measuring frequency
2 = Amplifier
3 = Electro-mechanical transducer
4 = Control valve
5 = Main servo-motor
6 = Nozzle of a Pelton turbine
7 = Generator
8 = Permanent-magnet generator

with all its principal elements. From this diagram the following relationship may be derived:

$$p(s) = \frac{1}{s\,T_H}\left\{\left[\Delta f\left(\frac{1}{\delta} + \frac{1}{\delta_b}\cdot\frac{s}{s+\dfrac{1}{T_b}}\right) + y\right] - p(s)\right\} \tag{1}$$

which can be reduced to a more convenient form

$$p(s) = \frac{\dfrac{1}{T_H}\left(1 + \dfrac{\delta}{\delta_b}\cdot\dfrac{s}{s+\dfrac{1}{T_b}}\right)}{s+\dfrac{1}{T_H}}\cdot\frac{\Delta f}{\delta} + \frac{\dfrac{1}{T_H}}{s+\dfrac{1}{T_H}}\cdot y \tag{2}$$

or $$p(s) = g_1(s)\cdot\frac{\Delta f}{\delta} + g_2(s)\cdot y \tag{3}$$

For the derivation of the properties which the correcting element must possess, the transfer function $g_2(s)$ with respect to the correcting condition of the system controller is important:

$$g_2(s) = \frac{\dfrac{1}{T_H}}{s+\dfrac{1}{T_H}} \tag{4}$$

Controller with temporary offset (Isodrome controller)

The main feature of this system is that it only takes into account the deviation of the system frequency from its desired value. The overall correcting condition is applied (again via amplifiers) to the main servo-motor, the position of which is fed back to the controller directly and also via a time-constant element. The main elements of the control circuit are shown in Fig. 2, from which the following relationship can be derived:

$$p(s) = \frac{1}{s\,T_H}\left\{\left[\frac{\Delta f}{\delta} + y\right] - p(s)\left[1 + \frac{\delta_v}{\delta}\cdot\frac{s}{s+\dfrac{1}{T_v}}\right]\right\}$$

which again can be reduced to a more convenient form, as

$$p(s) = \frac{\dfrac{1}{T_H}\left(s+\dfrac{1}{T_v}\right)}{s^2 + s\left[\dfrac{1}{T_v}+\dfrac{1}{T_H}\left(1+\dfrac{\delta_v}{\delta}\right)\right] + \dfrac{1}{T_H T_v}}\left(\frac{\Delta f}{\delta} + y\right) \tag{5}$$

In this case the transfer functions for the frequency deviation $g_1(s)$ and for the correcting condition of the system controller are identical

$$g_1(s) = g_2(s) = $$
$$= \frac{\dfrac{1}{T_H}\left(s+\dfrac{1}{T_v}\right)}{s^2 + s\left[\dfrac{1}{T_v}+\dfrac{1}{T_H}\left(1+\dfrac{\delta_v}{\delta}\right)\right] + \dfrac{1}{T_H T_v}} \tag{6}$$

Correcting the Response

As mentioned, for controlling parallel machines with the correcting condition (output) of the system controller, it is desirable to aim at the transfer function of the controller with acceleration influence having a uniform time constant T_{Hs}.

If there is a plant with an accelerometer controller, whose time constant differs from the intended value T_{Hs}, it is possible to effect a match by varying the gain in the path of the overall correcting condition applied to the main servo-motor. Since the characteristic of the control valve of the main servo-motor is designed for definite conditions, this does not always lead to success if the existing time constant T_H has to be increased to T_{Hs}. Moreover the control properties with respect to frequency may be expected to change.

If a change in the frequency control properties is acceptable, or even desirable on account of the unfavourable valve characteristic, the most convenient

method of arriving at a match is to introduce a feedback which takes into account the speed of adjustment of the main servo-motor (speed feedback). However, if the change in the frequency control properties is not admissible, the only possible solution is to employ a dynamic correcting element preceding the input of the correcting condition to the turbine governor, especially in those cases where, owing to hydraulic conditions, the response of the control system for "opening" and "closing" is made very different by valves in the oil brake.

Speed feedback

The transfer function of a turbine governor with an additional feedback r (s) is given by

$$p(s) = g_1(s)\,\frac{\Delta f}{\delta} + g_2(s)\,y - r(s) \qquad (7)$$

The feedback of the adjustment speed of the main servo-motor is introduced by the insertion of r $(s) = s\,T_R\,p(s)$, where T_R is the time constant of the speed feedback. Thus we may convert equation (7) into the following form

$$p(s) = \frac{g_1(s)}{1 + s\,T_R}\cdot\frac{\Delta f}{\delta} + \frac{g_2(s)}{1 + s\,T_R}\cdot y \qquad (8)$$

If only the effect on the transfer function for the controller output (correcting condition) is considered, equation (4) for the accelerometer controller assumes the form

$$g_2(s) = \frac{\dfrac{1}{T_H + T_R}}{s + \dfrac{1}{T_H + T_R}} \qquad (9)$$

while for the controller with temporary offset, equation (6) assumes the form

$$g_1(s) = g_2(s) =$$

$$= \frac{\dfrac{1}{T_H + T_R}\left(s + \dfrac{1}{T_v}\right)}{s^2 + s\left[\dfrac{1}{T_v} + \dfrac{1}{T_H + T_R}\left(1 + \dfrac{\delta_v}{\delta}\right)\right] + \dfrac{1}{(T_H + T_R)\,T_v}} \qquad (10)$$

As may be seen from the two equations (9) and (10), the effect of taking the speed feedback into account is to increase the time constant T_H to $(T_H + T_R)$. In the case of the accelerometer controller the previously stipulated requirement for a match when $T_{Hs} > T_H$ can be fulfilled when T_R is such that

$$T_{Hs} = T_H + T_R$$

In practice, though, a speed feedback can usually only be realized approximately. Therefore the conditions must be established under which the feedback of the approximate derivative of the position of the main servo-motor (opening) is sufficient.

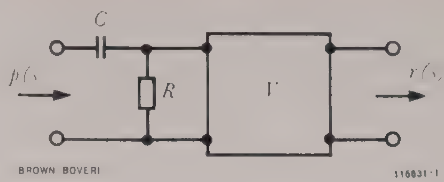


Fig. 3. – Circuit of the approximated speed feedback

$p(s)$ = Voltage corresponding to turbine opening
r (s) = Voltage corresponding to feedback
$T_r = RC$ = Time constant
V = Amplifier

From Fig. 3 the feedback is given by

$$r(s) = p(s)\cdot V\,\frac{s}{s + \dfrac{1}{T_r}} \qquad (11)$$

Substituting this value in equation (7) we obtain:

$$p(s) = \frac{g_1(s)}{1 + \dfrac{s\,V\,T_r}{1 + s\,T_r}}\cdot\frac{\Delta f}{\delta} + \frac{g_2(s)}{1 + \dfrac{s\,V\,T_r}{1 + s\,T_r}}\cdot y \qquad (12)$$

If we again consider only the effect on the transfer function for the correcting condition of the system controller, for the accelerometer controller equation (4) becomes:

$$g_2(s) = \frac{\dfrac{1}{T_H}\left(s + \dfrac{1}{T_r}\right)}{s^2 + s\left(\dfrac{1 + V}{T_H} + \dfrac{1}{T_r}\right) + \dfrac{1}{T_H\,T_r}} =$$

$$= \frac{\dfrac{1}{T_H}\left(s + \dfrac{1}{T_r}\right)}{\left(s + \dfrac{1}{T_1}\right)\left(s + \dfrac{1}{T_2}\right)} \qquad (13)$$

The transfer function (13) corresponds to that of the system with temporary offset in equation (6) when $T_r = T_v$ and $V = \delta_v/\delta$. It only remains to be established under what conditions the temporary offset behaves like a speed feedback.

Substituting $\varepsilon = \dfrac{T_r - T_2}{T_1 - T_2}$, equation (13) can be brought into the following form

$$g_2(s) = \frac{\frac{1}{T_1}(1-\varepsilon)}{s+\frac{1}{T_1}} + \frac{\frac{1}{T_2}\varepsilon}{s+\frac{1}{T_2}} \qquad (14)$$

This transfer function obviously approximates to that of the accelerometer controller, provided $\varepsilon \ll 1$, which is fulfilled when

$$\frac{4\,T_H T_r}{[T_H + (1+V)\,T_r]^2} \ll 1$$

Hence
$$g_2(s) \approx \frac{\frac{1}{T_H + (1+V)\,T_r}}{s + \frac{1}{T_H + (1+V)\,T_r}} \qquad (15)$$

The main time constant T_H of an accelerometer controller can thus be increased to

$$T_{H_s} = T_H + (1+V)\,T_r$$

by means of an approximated speed feedback, upholding the previously stipulated condition.

Dynamic correction element

If the given response of the turbine governor with respect to the correcting condition of the system controller

$$p(s) = g_2(s) \cdot y$$

is to be converted into the specified form

$$p_s(s) = \varphi_2(s) \cdot y$$

an element with the transfer function

$$\Psi(s) = \frac{\varphi_2(s)}{g_2(s)} \qquad (16)$$

must be inserted in the path of the correcting condition. This is known as the "dynamic correction element".

Dynamic correction element for accelerometer controllers

With the characteristic given by equation (4)

$g_2(s) = \dfrac{\frac{1}{T_H}}{s+\frac{1}{T_H}}$ and the stipulated characteristic

$$\varphi_2(s) = \frac{\frac{1}{T_{H_s}}}{s+\frac{1}{T_{H_s}}} \qquad (17)$$

the dynamic correction element according to equation (16) must have the following transfer function

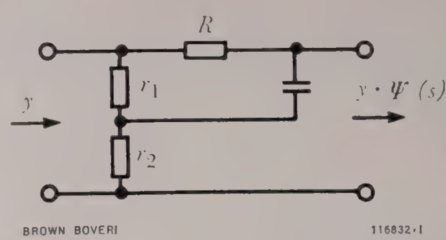


Fig. 4. – Circuit of the dynamic correction element for accelerometer controllers

$$\frac{r_2}{r_1+r_2} = \frac{T_H}{T_{H_s}}$$
$$RC = T_{H_s}$$

$$\Psi(s) = \frac{T_H}{T_{H_s}} \cdot \frac{s+\frac{1}{T_H}}{s+\frac{1}{T_{H_s}}} \qquad (18)$$

From the time function corresponding to equation (18)

$$\Psi(t) = \left(1-\frac{T_H}{T_{H_s}}\right)\left(1-e^{-\frac{t}{T_{H_s}}}\right) + \frac{T_H}{T_{H_s}} \qquad (19)$$

it is apparent how the internal circuitry of the dynamic correction element has to be arranged. Fig. 4 shows an example of this circuit.

Dynamic correction element for controllers with temporary offset

The characteristic given by equation (6), when compared with equation (17), can be represented in the following manner:

$$g_2(s) = \frac{\frac{1}{T_H}\left(s+\frac{1}{T_v}\right)}{\left(s+\frac{1}{T_1}\right)\left(s+\frac{1}{T_2}\right)} \qquad (20)$$

where

$$T_1 = \frac{T_H + \left(1+\frac{\delta_v}{\delta}\right)T_v}{2} + \sqrt{\left[\frac{T_H + \left(1+\frac{\delta_v}{\delta}\right)T_v}{2}\right]^2 - T_H T_v}$$

$$T_2 = \frac{T_H + \left(1+\frac{\delta_v}{\delta}\right)T_v}{2} - \sqrt{\left[\frac{T_H + \left(1+\frac{\delta_v}{\delta}\right)T_v}{2}\right]^2 - T_H T_v}$$

Let us assume the stipulated characteristic is given again by equation (17). Then the dynamic correction

element must have the following transfer function:

$$\Psi(s) = \frac{T_H}{T_{H_s}} \cdot \frac{\left(s - \frac{1}{T_2}\right)\left(s - \frac{1}{T_1}\right)}{\left(s + \frac{1}{T_v}\right)\left(s + \frac{1}{T_{H_s}}\right)} \tag{21}$$

or, allowing for the fact that $T_1 \cdot T_2 = T_H \cdot T_v$

$$\Psi(s) = \frac{T_2}{T_v} \cdot \frac{s + \frac{1}{T_2}}{s + \frac{1}{T_v}} \cdot \frac{T_1}{T_{H_s}} \cdot \frac{s + \frac{1}{T_1}}{s + \frac{1}{T_{H_s}}} = \Psi_1(s) \cdot \Psi_2(s) \tag{22}$$

In this case it is apparent that realization of the dynamic correction requires two independent circuits.

By means of $\Psi_1(s)$ the transfer function is converted into one for an accelerometer controller with a time constant of $T_H = T_1$ and with $\Psi_2(s)$ the conversion from T_1 to T_{H_s} is effected.

The time functions corresponding to $\Psi_1(s)$ and $\Psi_2(s)$

$$\Psi_1(t) = \left(1 - \frac{T_2}{T_v}\right)\left(1 - e^{-\frac{t}{T_v}}\right) + \frac{T_2}{T_v}$$

$$\Psi_2(t) = \left(1 - \frac{T_1}{T_{H_s}}\right)\left(1 - e^{-\frac{t}{T_{H_s}}}\right) + \frac{T_1}{T_{H_s}}$$

show how the circuitry of the dynamic correction element has to be arranged. Fig. 5 gives an example of this circuit.

Results of Measurements

Accelerometer controller with speed feedback (experiments on an analogue computer)

For a turbine-generator set with an accelerometer controller the following data were determined at fixed frequency:

- Time constant for opening $T_{H+} = 7{\cdot}5$ s, for closing $T_{H-} = 4$ s when the correcting condition was abruptly changed by $\pm$ 10% of its maximum value.
- Minimum value of the change in correcting condition for opening $\Delta y_+ = 13{\cdot}6\%$, for closing $\Delta y_- = 16\%$, resulting in the maximum adjustment speed of the main servo-motor at the start of the control process (limit of dynamic linearity).

The figures stipulated for matching when employed with other installations in an interconnected system with a central system controller were

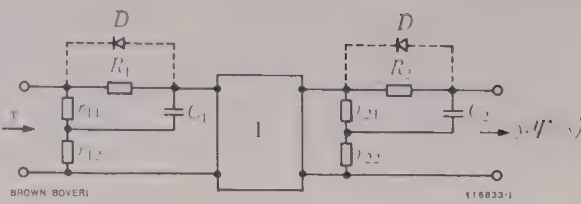


Fig. 5. – Circuit of the dynamic correction element for accelerometer controllers

$$\frac{r_{12}}{r_{11} + r_{12}} = \frac{T_2}{T_v} \qquad R_1C_1 = T_v$$

$$\frac{r_{22}}{r_{21} + r_{22}} = \frac{T_1}{T_{H_s}} \qquad R_2C_2 = T_{H_s}$$

1 = Amplifier

D = Diodes for asymmetric response

$$\left.\begin{array}{l} T_{H+} \\ T_{H-} \end{array}\right\} = 12 \text{ to } 18 \text{ s and } \Delta y_\pm > 20\%$$

By introducing an approximated speed feedback with $T_r = 1$ s and $V = 9$, it was possible to modify the data of the installation to the following figures

$$T_{H+} = 17{\cdot}5 \text{ s} \qquad \Delta y_+ = 32\%$$

$$T_{H-} = 14{\cdot}5 \text{ s} \qquad \Delta y_- = 58\%$$

which comply with the stipulated limits.

In Fig. 6 the variation of the machine output with respect to time, resulting from an abrupt change of correcting condition of $\Delta y = \pm$ 20% with and without speed feedback, can be seen from oscillograms recorded with an analogue computer. It will be observed that the dynamic limit of linearity is not exceeded with the speed feedback.

Controller with temporary offset and dynamic correction element (Service measurements in a power station)

The problem in this particular case was that a pair of turbine-generator sets with temporary offset in one station had to be connected in parallel with two other stations equipped with accelerometer controllers, to produce a joint tie-line power. The response of the first machines differed appreciably from that of the others. By evaluating a large number of oscillograms recorded with different turbine openings and abrupt changes in the correcting condition, the mean time function of the machine output was determined for both machines (Fig. 7), from which the approximate transfer function could be established. On opening there was a pronounced temporary offset in the characteristic; for closure by means of a valve incorporated in the oil brake the character-

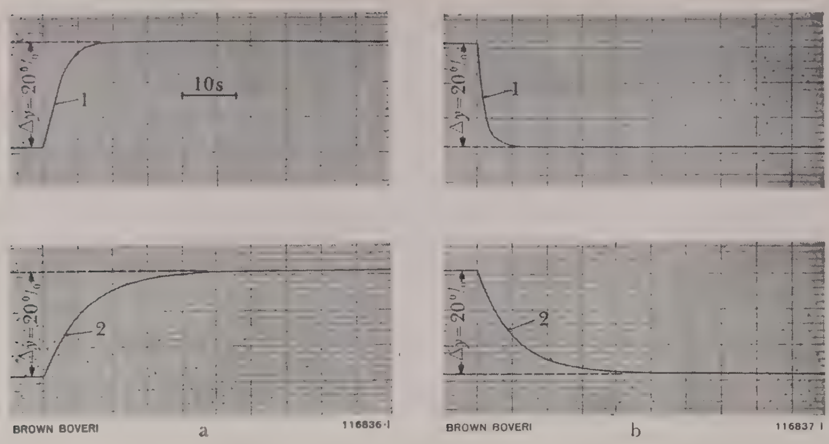


Fig. 6. – Effect of the approximate speed feedback on an accelerometer controller

a: Output when the correcting condition changes abruptly by $\Delta y = +20\%$

b: Output when the correcting condition changes abruptly by $\Delta y = -20\%$

1 = Without speed feedback

2 = With speed feedback

t = Time

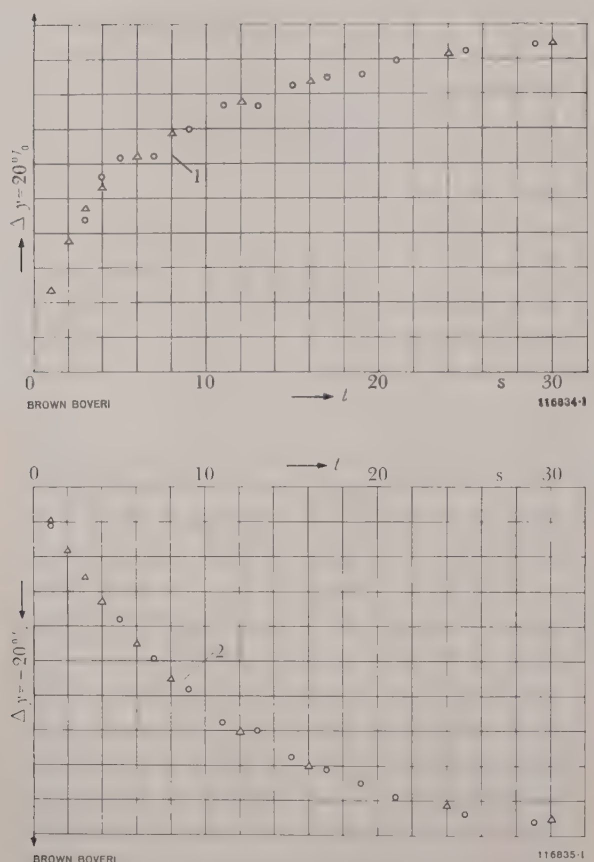


Fig. 7. – Measured and calculated mean time function of the outputs of two turbine-generator sets with temporary offset

1 = Output when correcting condition changes abruptly by $\Delta y = +20\%$

2 = Output when correcting condition changes abruptly by $\Delta y = -20\%$

○ = Measured values

△ = Calculated values

t = Time

istic approached that of an accelerometer controller. The data are tabulated below:

Opening	Closing
$g_2(s)$ as per eqn. (6) or (20) $T_{H+} = 3{\cdot}3$ s, $T_1 = 12$ s $T_v = 5{\cdot}8$ s, $T_2 = 1{\cdot}6$ s $\frac{\delta_v}{\delta} = 0{\cdot}8$	$g_2(s)$ as per eqn. (4) $T_{H-} = 11$ s

Fig. 7 shows the mean time functions according to the measurements and those obtained from the equivalent transfer functions.

For matching, the response of an accelerometer controller was stipulated as follows, for opening and closing, respectively:

$$15\text{ s} < T_{H+} < 22\text{ s and } 15\text{ s} < T_{H-} < 22\text{ s}$$

Owing to the fact that the response for closure was rather close to the permissible limit, it was necessary to arrange the circuitry of the dynamic correction element in such a way that it is practically ineffective when the correcting condition decreases, whereas its effect corresponds to $\Psi(s)$ as in equation (21) when the correcting condition is increasing. This stipulation was realized with the correction circuit shown in Fig. 5, employing the diodes shown dotted therein. The effect of the dynamic correction element is demonstrated by the oscillograms in Fig. 8.

It is worth pointing out that the insertion of this correction element almost completely eliminated fluctuation of water pressure and rotor oscillations.

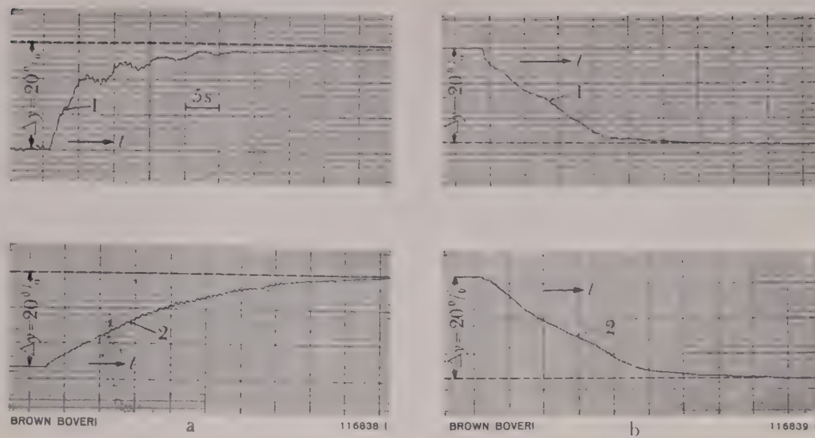


Fig. 8. – Effect of the dynamic correction element on a controller with temporary offset

a: Output when correcting condition changes abruptly by $\Delta y = + 20\%$

b: Output when correcting condition changes abruptly by $\Delta y = - 20\%$

1 = Without dynamic correction element

2 = With dynamic correction element

t = Time

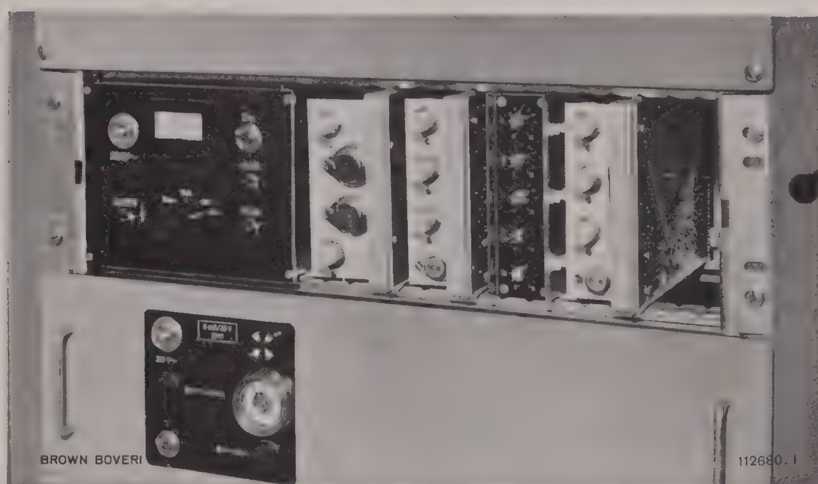


Fig. 9. – Transistorized dynamic correction element

Front view with front panel removed. With the setting facilities provided it is possible to adjust the correction function within wide limits.

Operational Experience

In a power station with two turbine sets rated 45 MW a transistorized correction element has been in service for several months in conjunction with controllers having temporary offset. The correcting condition is provided by a central system controller and conveyed via telemetering channels to this station and two others, each with one machine set producing a controlling power of 45 MW. All three stations are connected to a common transfer point.

The response of the machine sets with temporary offset was so extreme before the dynamic correction element was inserted (see the Table opposite) that load oscillation occurred when the station was paralleled with the others, employing a rate of adjustment appropriate to primary control. On inserting the correction element (Fig. 9) the response was adapted to that of the machines with accelerometer controllers so accurately that, even at maximum control speed, the load distribution between the individual generating stations during the control process was practically the same as in the steady state.

Conclusions

The introduction of primary control to large interconnected power systems has to overcome the difficulty of having to severely slow down the control elements or even resort to the inherently sluggish secondary control in view of the possible instability when generating stations with dissimilar responses have to run in parallel. By employing dynamic correction elements which convert a correcting command coming from a central system controller, it is possible to achieve stable operation without having to make any changes in the actual responses of the individual turbine governors. Thus full advantage can be taken of the benefits accruing from primary control, such as higher control speed and more rapid correction of quite appreciable load surges, even in large interconnected systems.

(KME) H. Bloch

THE ANALYSIS OF COMPOUND AUTOMATIC CONTROL SYSTEMS BY MEANS OF CONFORMAL MAPPING, ILLUSTRATED BY THE EXAMPLE OF A THERMODYNAMIC MACHINE

621.53

Thermodynamic plants such as industrial turbines, compressors and steam generators are frequently fitted with compound control systems, as opposed to the usual single-loop systems. Compound systems are those in which additional feedbacks are added to single-loop circuits to improve the quality of the control. Alternatively, compound systems are of multiple nature, controlling a number of conditions simultaneously. Additional couplings may be introduced to reduce the interaction between the controlled variables. This gives rise to extremely complicated structural diagrams. The behaviour of such multiple-loop systems may be completely different to that of single-loop systems. It becomes desirable to use an analysis which extends beyond the question of stability.

The method of conformal mapping of the p-plane, using the transfer function of the broken system (p = Laplace operator as complex frequency $\delta + i\omega$) yields all eigen values of the closed system, as well as the static behaviour at the point at which the system is broken. Stability criteria are dispensed with. It is necessary to use a digital computer on account of the extensive calculation required for the conformal mapping. The control of the delivery pressure of a blast furnace compressor is taken as an example to demonstrate the method.

THE PROBLEMS of the single-loop control circuit of linear behaviour have today largely been solved. The knowledge of this circuit, gained in the course of innumerable investigations and tests during a number of decades, is apparently insufficient for dealing with compound systems, and in particular with multiple controls. The reason for this is that the behaviour of a dependent system is not the sum of the characteristics of the independent individual circuits. The dependent system must be considered as completely new. The behaviour resulting from the addition of a new controlled variable to a multiple control system is not necessarily similar to that which the system previously revealed. Conclusions regarding the properties of the complete system can therefore not be reached from a knowledge of the behaviour of the individual circuits. The rules of behaviour of single-loop circuits may be completely reversed in the case of multiple control. For example, controlled variables in multiple control systems have different characteristics to those which would correspond to the setting of their proportional controllers [1] [1] (linear differential equations with constant coefficients are assumed throughout); as another example, the larger the proportional band of a controller in a corresponding system, the poorer its stability [2].

In dealing with compound control systems, it is necessary to be free of preconceptions from the field of single-loop circuits. It is also desirable to find a systematic approach in order to deal with the vast number of possible combinations.

If an attempt is made to investigate the stability of compound circuits by means of the frequency response ($p = i\omega$) a generalisation of the Nyquist criterion [3] is unavoidable, since the frequency response in such systems may take completely unconventional forms [1], [2]. But the generalised statement, as is well known, requires the number of poles in the right-hand p-half-plane (p = complex frequency $\delta + i\omega$) of the transfer function, or, in other words, the number of unstable roots of the system assumed blocked at the entry of that break point at which the frequency response is expressed. In certain circumstances, this considerably complicates the application of this criterion.

Since, furthermore, the stability is not the only important quality of the control system, and for

[1] The figures in brackets refer to the bibliography on p. 769.

example the transients in the event of external disturbances or reference inputs must also be considered, the system must be investigated in a way which yields all its eigen values. The extension of the idea of Dzung [4], namely the complete conformal mapping of the transfer function of the system, is an all-embracing method which, besides giving the eigen values of a system, provides an insight into the static behaviour in the case of varying loop parameters and into the dynamic structure in the case of a synthesis. This conformal mapping yields as many sheets of the Riemann surface as given by the order of the system, provided the condition for its application is fulfilled, namely the Cauchy-Riemann differential equations are satisfied [5]. Thus all eigen values of the system without external influence appear at the critical point $+1$. Therefore insight is gained into the behaviour in the event of disturbance (resonance) or caused by the reference input. The transformation of the origin of the p-plane also yields the static behaviour in function of loop parameters to be considered.

It must be mentioned that the work involved in this method becomes considerable if a number of coefficients (controller gains, reset times, time constants and derivative factors, etc.) are to be varied. The use of digital computers, however, renders such investigations possible. It is essential to check the partial results carefully, because the probability of mistakes increases with the complexity of the system. The analogue computer can frequently be used to gain essential indications (e.g. where the broken system has unstable roots), or to confirm calculated results (critical gains). However, the method of calculation varies considerably between these two computers, even when the aims are similar, just as the computers themselves are completely different.

It was possible to carry out the calculations for the conformal mapping in the case of the control system discussed here on the Zebra computer of the Centre de Calcul Electronique de l'Ecole Polytechnique of Lausanne University.

Method and Example

The present problem is the control of the delivery pressure of the turbo-compressor for a blast furnace in a steelworks. Fig. 1 shows the simplified control diagram of the installation. The output pressure of the controller R_p influences the desired-value setting of the speed governor via the hydraulic adjusting mechanism. At the full-load point, which we are considering here, the anti-surge control is not in action. It is therefore left out of the investigation.

The speed governor R_n is a controller with proportional action of high natural frequency. The pressure controller R_p is the Brown Boveri Model M 50, which generally has a proportional and a proportional-integral action. The structural diagram of this controller consists of a rapid, integral forward component and a permanent and temporary feedback component.

The conformal mapping discussed is confined to the case of variation of the pressure controller and

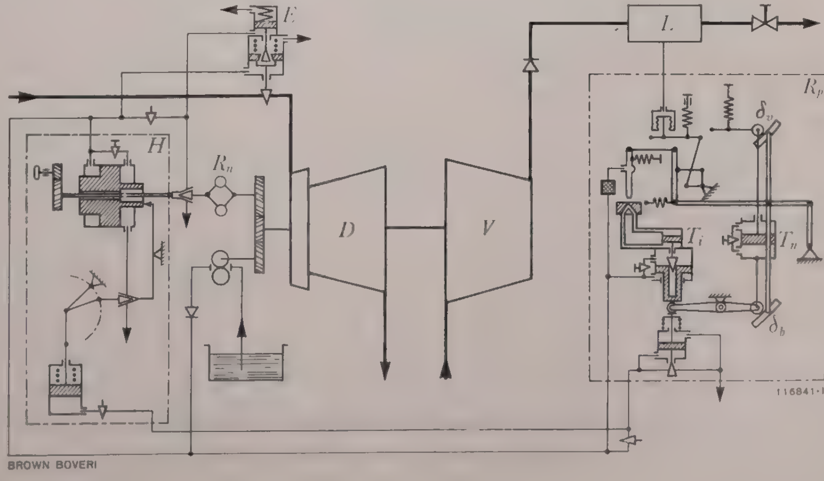


Fig. 1. – Simplified control diagram of a compressor driven by a turbine

D = Steam turbine
V = Compressor
L = Pipe lines
R_n = Speed governor
R_p = Pressure controller M 50
H = Hydraulic adjustment of the speed governor
E = Governing valves (operating successively)

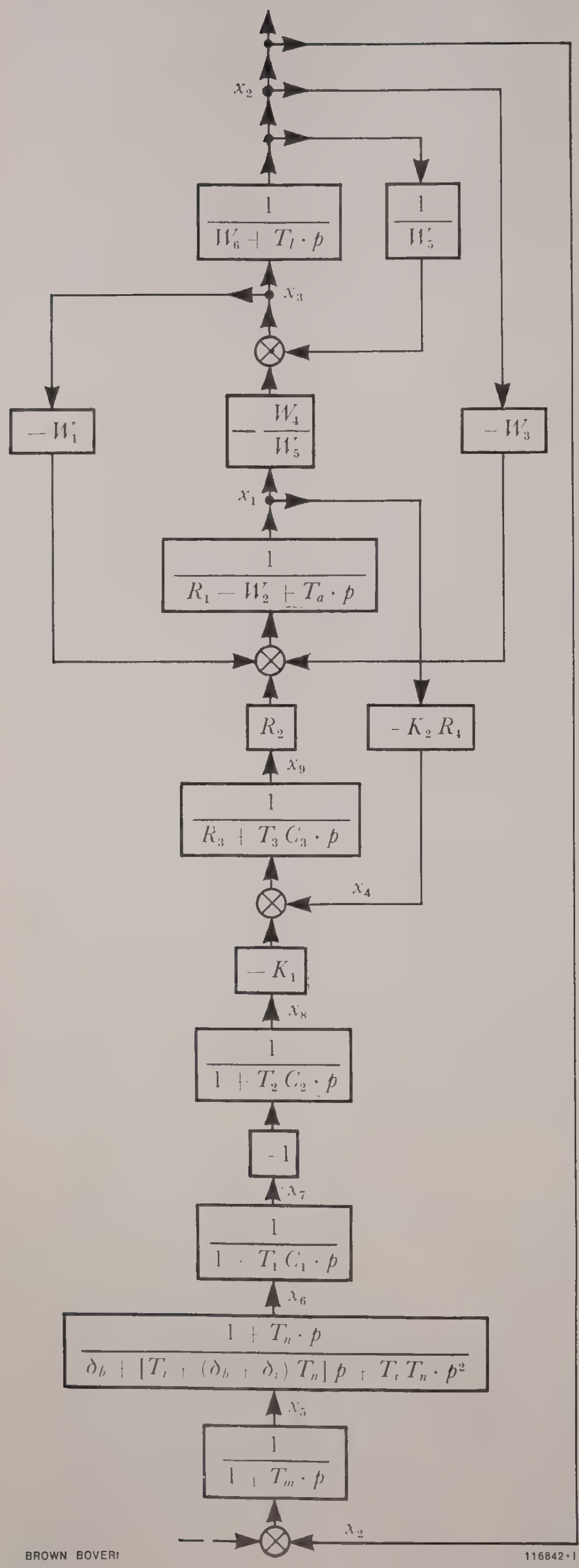


Fig. 2. – Structure diagram of the installation according to Fig. 1

assumes an ideal proportional controller and an ideal integral controller. In the mathematical treatment, using the transfer function of the M 50 controller, the appropriate parameters are equated to zero.

The following is the system of differential equations of the diagram according to Fig. 1:

For the compressor and the delivery duct [6]:

$$(R_1 - W_2)\, x_1 + T_a\, x_1' = R_2 x_9 - W_1 x_3 - W_3 x_2 \qquad (1)$$
$$x_2 = W_4 x_1 + W_5 x_3 \qquad (2)$$
$$x_3 = W_6 x_2 + T_l x_2' \qquad (3)$$

For the hydraulic governor adjustment, the speed governor and the steam inlet valves:

$$-K_1\, x_8 + x_4 = R_3\, x_9 + T_3 C_3 x_9' \qquad (4)$$
$$x_4 = -K_2 R_4 x_1 \qquad (5)$$
$$x_6 = x_7 + T_1 C_1 x_7' \qquad (6)$$
$$-x_7 = x_8 + T_2 C_2 x_8' \qquad (7)$$

For the measuring device with the pressure measuring connection and the pressure controller:

$$x_2 = x_5 + T_m x_5' \qquad (8)$$

$$-\left[\frac{1}{T_n}\int x_5\, \mathrm{d}t + x_5\right] = \qquad (9)$$
$$= \frac{\delta_b}{T_n}\int x_6\, \mathrm{d}t + \left[\frac{T_i}{T_n} + \delta_b + \delta_v\right] x_6 + T_i x_6'$$

The coefficients of these equations have not been given in full; in most cases they are not linear and they are frequently of very complicated structure. In (1), (2) and (3) they depend on the controlled conditions, on the configuration of the compressor set at the load under consideration, on the expansion conditions of the steam in the valves and in the turbine, on the polytropic compression behaviour of the air, and on the storage capacity in the path from the compressor through the pre-heater to the blast furnace. The coefficients of the equations (4) to (7) take into account the kinematics and dynamics of the speed governor, the hydraulic governor adjustment and the steam inlet valves. The non-linearity of these coefficients arises largely from Bernoulli's equation.

The structural diagram of the installation, as shown in Fig. 2, is obtained from the Laplace transform of these equations (1) to (9). The incremental

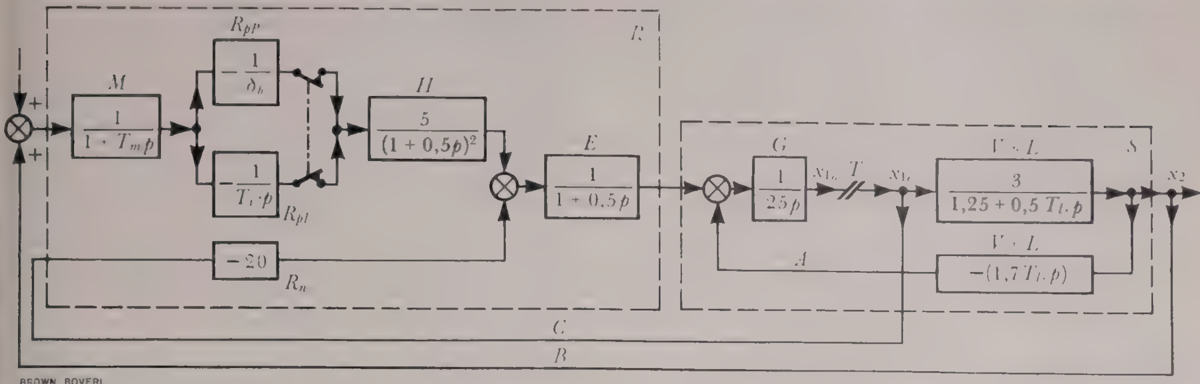


Fig. 3. – *Structure diagram shown in Fig. 2 after elimination of x_3*

R = Controller M = Pressure measuring pipe and measuring unit of the pressure controller R_{pP} = Proportional pressure controller
S = Process G = Compressor set R_{pI} = Integral pressure controller

deflections from the steady state conditions are indicated by:

x_1 = speed
x_2 = delivery pressure
x_3 = delivery volume
x_4 = output of the speed governor
x_5 = output of the pressure measuring device
x_6 = output of the pressure controller
x_7 = displacement of the pilot piston of the hydraulic speed governor adjusting device
x_8 = displacement of the power piston of the hydraulic speed governor adjusting device
x_9 = valve displacement

and

T_i = forward integration time of the M50 controller
T_n = reset time of the M50 controller
δ_b = permanent feedback of the M50 controller
δ_v = temporary feedback of the M50 controller

For the sake of simplification x_3 was eliminated from the equations (1) to (9). The resulting structural diagram is shown in Fig. 3. The values of the coefficients, rendered linear, as they arose at the full-load point of the plant have been used.

The fundamental structure of the system is readily visible; one loop with the controlled variable x_2 and an auxiliary controlled variable x_1. The feedback (A) is a part of the process itself and represents the influence of the compressor and delivery line. Loop (A) can be broken only in theory.

In order to assess the functioning of all three loops A, B and C, by means of a single transfer function, the system was broken at the unconventional point T (speed). We designate the transfer function as resultant frequency response in function of

$$p = \delta + i\omega, \text{ referred to as } G_{res}(p).$$

The condition for closing at point T is:

$$\frac{x_{1a}}{x_{1e}} = G_{res}(p) = +1 \qquad (10)$$

If we now map the p-plane, using $G_{res}(p)$ as transfer function, the solutions which satisfy equation (10) appear at the critical point $+1$. These are the eigen values of systems (1) to (9) and they signify the complex frequencies of the oscillations which the closed system is capable of performing. (In the analogue computer these solutions appear implicit in the sum of exponential functions, which is furthermore dependent upon the initial conditions.) Since (p) is complex the function $G_{res}(p)$ was split into real and imaginary parts so that it could be fed into the digital computer (e.g. with the Horner's scheme as sub-routine this work can be avoided). $G_{res}(p)$ rationalized now consists of a real part $R_{res}(\delta, \omega)$ and an imaginary part $I_{res}(\delta, \omega)$:

$$\left.\begin{aligned} R_{res} &= R_I + R_{II} + R_{III} \\ I_{res} &= I_I + I_{II} + I_{III} \end{aligned}\right\} \qquad (11)$$

The following substitutions are applicable:

$$R_I = -\frac{8}{5} \cdot \frac{1}{(\delta^2+\omega^2)\,[(2+\delta)^2+\omega^2]} \cdot (2\delta+\delta^2-\omega^2)$$

$$\mathrm{I_I} = +\frac{8}{5} \cdot \frac{1}{(\delta^2+\omega^2)\,[(2+\delta)^2+\omega^2]} \cdot 2\,\omega\,(1+\delta)$$

$$\mathrm{R_{II}} = -\frac{12}{25} \cdot$$

$$\cdot \frac{8{\cdot}5\,\delta + 8{\cdot}4\,T_l\delta^2 + 1{\cdot}6\,T_l\omega^2 + 2\,T_l^2\delta^3 + 2\,T_l^2\delta\,\omega^2}{(\delta^2+\omega^2)\,[(5+2\,T_l\delta)^2+4\,T_l^2\omega^2]}$$

$$\mathrm{I_{II}} = +\frac{12}{25}\,\omega\,\frac{8{\cdot}5 + 6{\cdot}8\,T_l\delta + 2\,T_l^2\delta^2 + 2\,T_l^2\omega^2}{(\delta^2+\omega^2)\,[(5+2\,T_l\delta)^2+4\,T_l^2\omega^2]}$$

$$\mathrm{R_{III}} = \mathrm{R_{IV}}\,\mathrm{R_M} - \mathrm{I_{IV}}\,\mathrm{I_M} \qquad \mathrm{I_{III}} = \mathrm{I_{IV}}\,\mathrm{R_M} + \mathrm{R_{IV}}\,\mathrm{I_M}$$

$$\mathrm{R_{IV}} = E\,(AC - BD) \qquad \mathrm{I_{IV}} = -\,E\,(BC + AD)$$

$$A = (5\,\delta + 2\,T_l\delta^2 - 2\,T_l\omega^2)\,(1 + T_m\delta) - \\ -\,\omega^2\,T_m\,(5 + 4\,T_l\delta)$$

$$B = \omega\,[5\,T_m\delta + 2\,T_l\,T_m\delta^2 - 2\,T_l\,T_m\omega^2 + \\ +\,(5 + 4\,T_l\delta)\,(1 + T_m\delta)]$$

$$C = (2+\delta)\,[(2+\delta)^2 - 3\,\omega^2]$$

$$D = \omega\,[3\,(2+\delta)^2 - \omega^2]$$

$$E = -\frac{96}{5} \cdot \frac{1}{\delta^2+\omega^2} \cdot \frac{1}{(5+2\,T_l\delta)^2 + 4\,T_l^2\omega^2} \cdot$$

$$\cdot \frac{1}{[(2+\delta)^2+\omega^2]^3} \cdot \frac{1}{(1+T_m\delta)^2 + T_m^2\omega^2}$$

$$\mathrm{R_M} = \frac{Z_R}{N} \qquad \mathrm{I_M} = \frac{Z_I}{N}$$ Transfer function of the M50 controller.

$$Z_R = (\delta\,T_n + 1)\cdot \\ \cdot\Big\{(\delta^2-\omega^2)\,T_i\,T_n + \delta\,[T_i + (\delta_b+\delta_v)\,T_n] + \delta_b\Big\} + \\ +\,\omega^2\,T_n\,[2\,\delta\,T_i\,T_n + T_i + (\delta_b+\delta_v)\,T_n]$$

$$Z_I = \omega\Big[\,T_n\Big\{(\delta^2-\omega^2)\,T_iT_n + \delta\,[T_i + (\delta_b+\delta_v)\,T_n] + \delta_b\Big\} - \\ -\,[2\,\delta\,T_i\,T_n + T_i + (\delta_b+\delta_v)\,T_n]\,(\delta\,T_n+1)\Big]$$

$$N = \Big\{(\delta^2-\omega^2)\,T_i\,T_n + \delta\,[T_i + (\delta_b+\delta_v)\,T_n] + \delta_b\Big\}^2 + \\ +\,\omega^2\Big\{2\,\delta\,T_i\,T_n + T_i + (\delta_b+\delta_v)\,T_n\Big\}^2$$

Parameters to be varied have been retained in algebraic form in these equations, as

δ = Damping

ω = Angular velocity

T_l = Filling time of the delivery pipe-work

T_m = Filling time of the measuring device, with the pressure measuring pipe to the pressure controller

T_i, T_n, δ_b and δ_v as variables of the M50 controller.

Here, as mentioned, we are only concerned with the ideal proportional controller, and the ideal integral controller. For the former we substitute $T_i = 0$, $T_n = 0$ (alternatively $\delta_v = 0$), for the integral controller δ_b and $\delta_v = 0$.

This took place when the parameters were fed into the computer. The complete investigation embraced the ideal proportional-integral controller (at $T_i = 0$ and $\delta_b = 0$), the M50 controller, and the variations of T_l and T_m. Discussion of these results would render the explanation rather tedious.

In carrying out the conformal mapping, i.e. the transfer of the p-plane by means of the function $G_{res}(p)$ the following points were observed:

At point + 1 the mapping encompasses as many sheets, folded at branch points (Riemann surfaces[1]), as the order of the system. If it is uneven, there is at least one real solution. The remaining eigen values are either also real or conjugate complex. Since, however, negative and positive frequencies are conjugate and as the mapping is symmetrical on the real axis, respecting the positive and negative frequencies, it is sufficient to map only the upper half of the p-plane including its real axis ($\omega \geqslant 0$). The mapping of the real axis $G_{res}(p)\,|_{p=\delta}$ yields the number of real solutions, through equation (10).

$$G_{res}(p)\,|_{p=\delta,\ \omega=0} = +1 \qquad (12)$$

The total number of solutions (order of the system) less the real solutions found by means of (12), gives the number of pairs of conjugate complex solutions. The next objective is to find them by conformal mapping.

If $G_{res}(p)\,|_{p=0}$ remains finite, which is not the case here, even for the proportional controller, due to neglecting the difference R_1–W_2 in equation (1), this expression indicates the static behaviour of the system at the break concerned [1].

Mappings

The present representations are, in effect, restricted to three mappings. In these, equation (10) was completely solved. Emphasis was laid upon the demonstration value of the diagram because the method here is of more interest than the critical examination of the control system.

To start with, a number of functions $G_{res}(p)\,|_{p=i\omega}$ are shown, keeping $T_l = 4$ and $T_m = 0{\cdot}5$ in all the diagrams; firstly with variation of the gain $K_7 = \dfrac{1}{\delta_b}$

[1] See pages 108–34 of [5].

on the proportional controller, for values $K_7 = 2$, 4 and 8, then with variation of the integral controller for integration times $T_i = 16$, 4, 2, 1 and 0·5. The equation (10) is then solved by mapping for $K_7 = 4$ and $T_i = 4$ and 16 seconds, i.e. all eigen values of this equation are sought. For the proportional controller the order of (10) is the 6th, for the integral controller the 7th.

The synthesis of the system according to Fig. 3 consists of the addition of loops *A* and *A plus B* to the circuit *C*. Circuit *C* alone signifies the speed governing of the turbine with its integral behaviour, without the influence of compression in the compressor. This circuit includes the inertia of the compressor, but not its influence on the controlled variable x_1. The second-order mapping, corresponding to the transfer function of this circuit, is the net drawn in full lines in Fig. 4. The solution of equation (10) can be read off at point $+1$ as $p_1 = -1 + 0{\cdot}76\,i$, the second solution is its conjugate complex partner $p_2 = -1 - 0{\cdot}76\,i$.

If loop *A* is now considered (inherent feedback of the plant, which caused the integral action compressor set to assume a proportional action) we have the case of the speed governing, as it arises in the installation shown in Fig. 1 when the pressure controller R_p is out of action. The net drawn in dotted lines in Fig. 4 is the corresponding mapping of 3rd order. $p_{1,2} = -1{\cdot}12 \pm 0{\cdot}9\,i$ are the physically important solutions. The 3rd real solution is negative. The effect of the compressor with the delivery pipework $T_l = 4$ is to stabilize and raise the frequency. The addition of loop *B* finally yields the complete plant.

The effect of this loop, i.e. the pressure control, is added to the dotted net in Fig. 4, just as the dotted net was the result of adding loop *A* to the fully lined net. The addition is visible in the equation (11). Fig. 5 shows the resulting frequency responses $G_{res}(p)\,|_{p=i\omega}$ for the proportional controller with $K_7 = 2$, 4 and 8. They show that $K_7 = 5{\cdot}2$ (or $\delta_b = 19{\cdot}2\,\%$), is the approximate stability limit, with $\omega = 0{\cdot}88$. The control action is fairly rapid with relatively low gain.

The family of curves $G_{res}(p)\,|_{p=i\omega}$, drawn for the integral controller ($T_i = 16$, 4, 2, 1 and 0·5) is shown in Fig. 6. The time $T_i = 1$ is the stability limit at $\omega \sim 0{\cdot}385$. A slow control action results with a relatively rapid controller.

A number of damping lines are drawn in for Fig. 5 for $K_7 = 2$ ($\delta_b = 50\,\%$), in Fig. 6 for $T_i = 2$. Compared with Fig. 4, the considerable extension and deformation of the parameter net in the direction of deteriorating stability is particularly noticeable in Fig. 6.

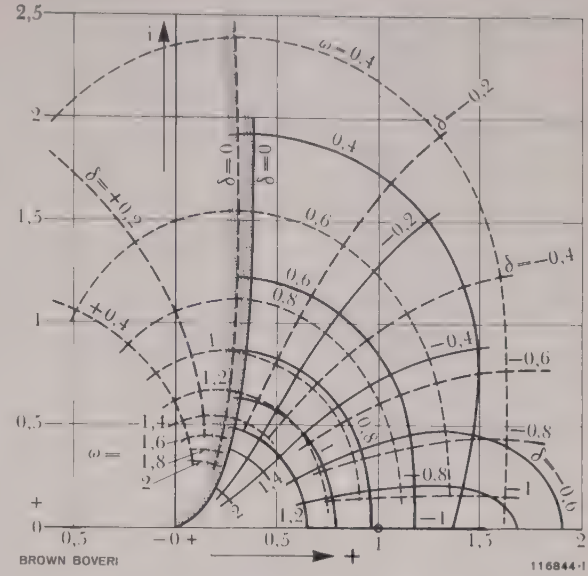


Fig. 4. – Conformal mapping of loop C (full lines) and of the loops C and A (dotted lines), as shown in Fig. 3

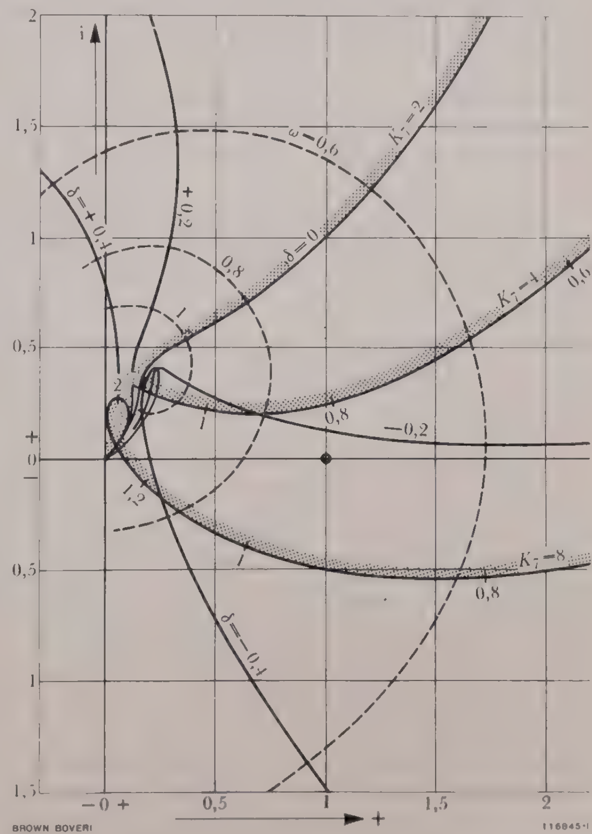


Fig. 5. – Frequency response curves of the installation with proportional pressure controller ($K_7 = 2$, 4 and 8)

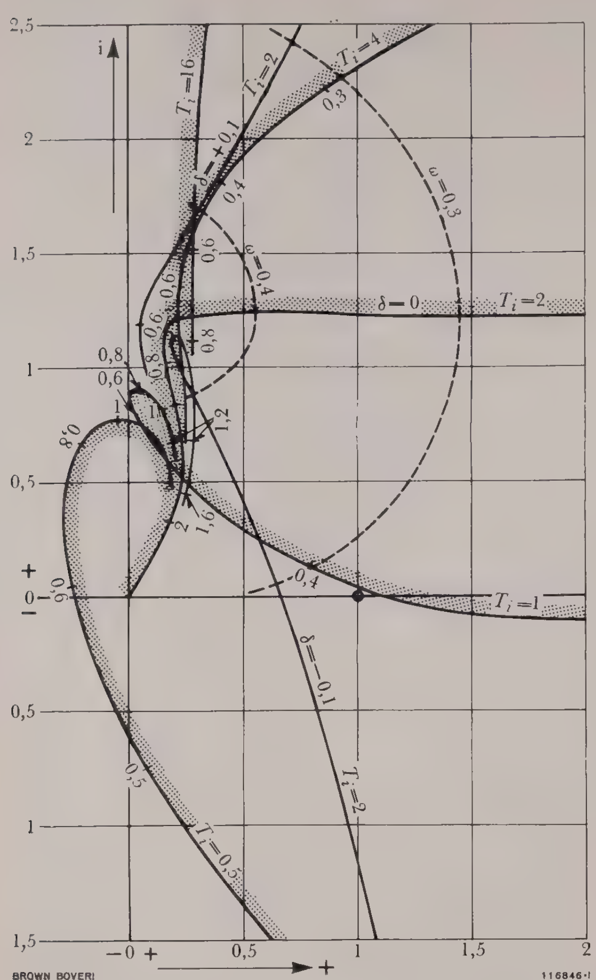
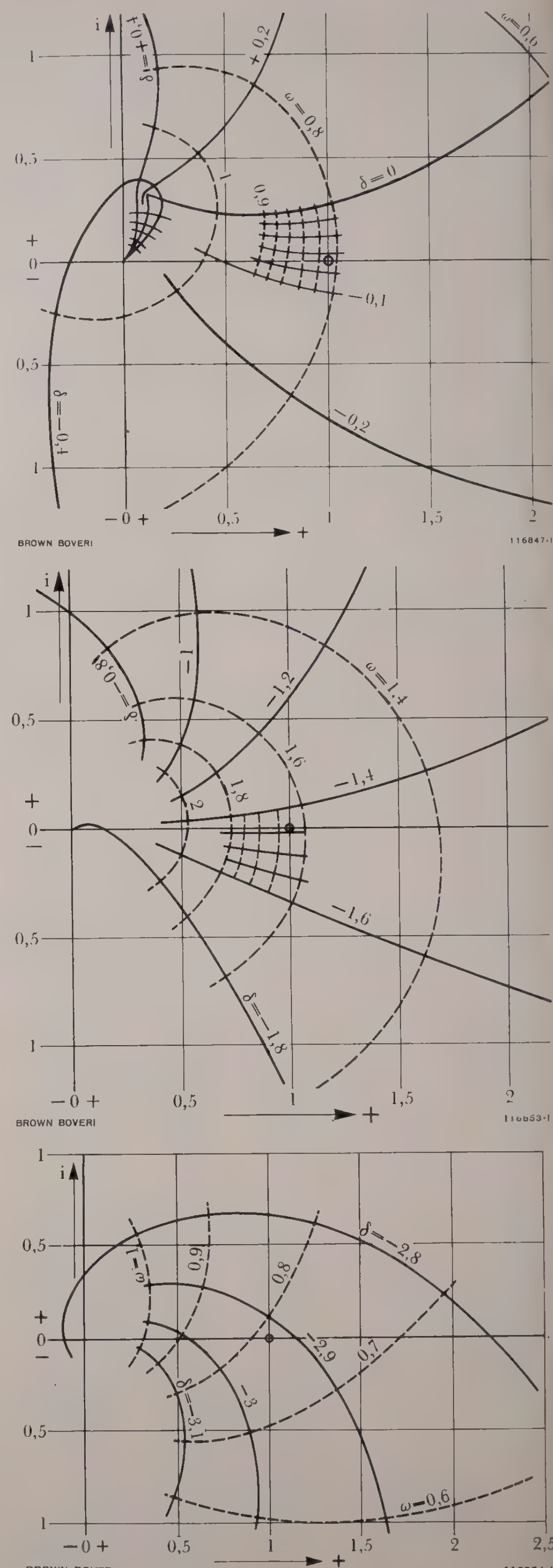


Fig. 6. – Frequency response curves of the installation with integral pressure controller (T_i = 16, 4, 2, 1 and 0·5)

As a rule it can no longer be assumed, in the case of compound system, that the distance of the frequency $G_{res}(p)\,|_{p=i\omega}$ from the critical point + 1, with due regard to the ω-parameter, is a measure of the stability. The mappings also vary considerably with the choice of the break T (except in the immediate neighbourhood of + 1) which may lead to considerably varying estimates.

Fig. 7 (a), (b) and (c) and 8 show the plots and solutions for the installation with the proportional controller at K_7 = 4. At no point does the plot of



a

b

c

Fig. 7. – Conformal mapping of the p-plane for the installation with proportional-acting controller for K_7 = 4

a: Part of mapping for reading off p_1 and p_2

b: Part of mapping for reading off p_3 and p_4

c: Part of mapping for reading off p_5 and p_6

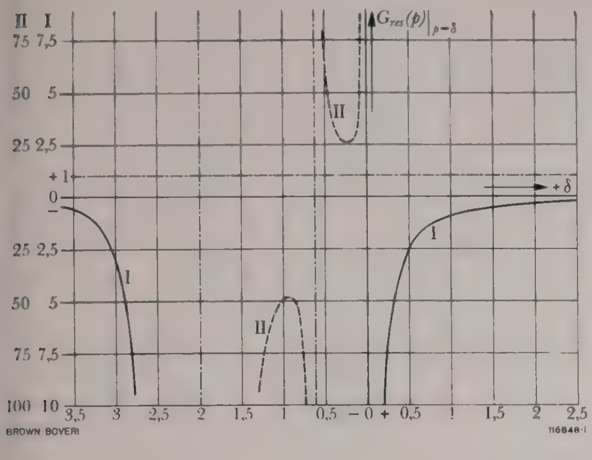


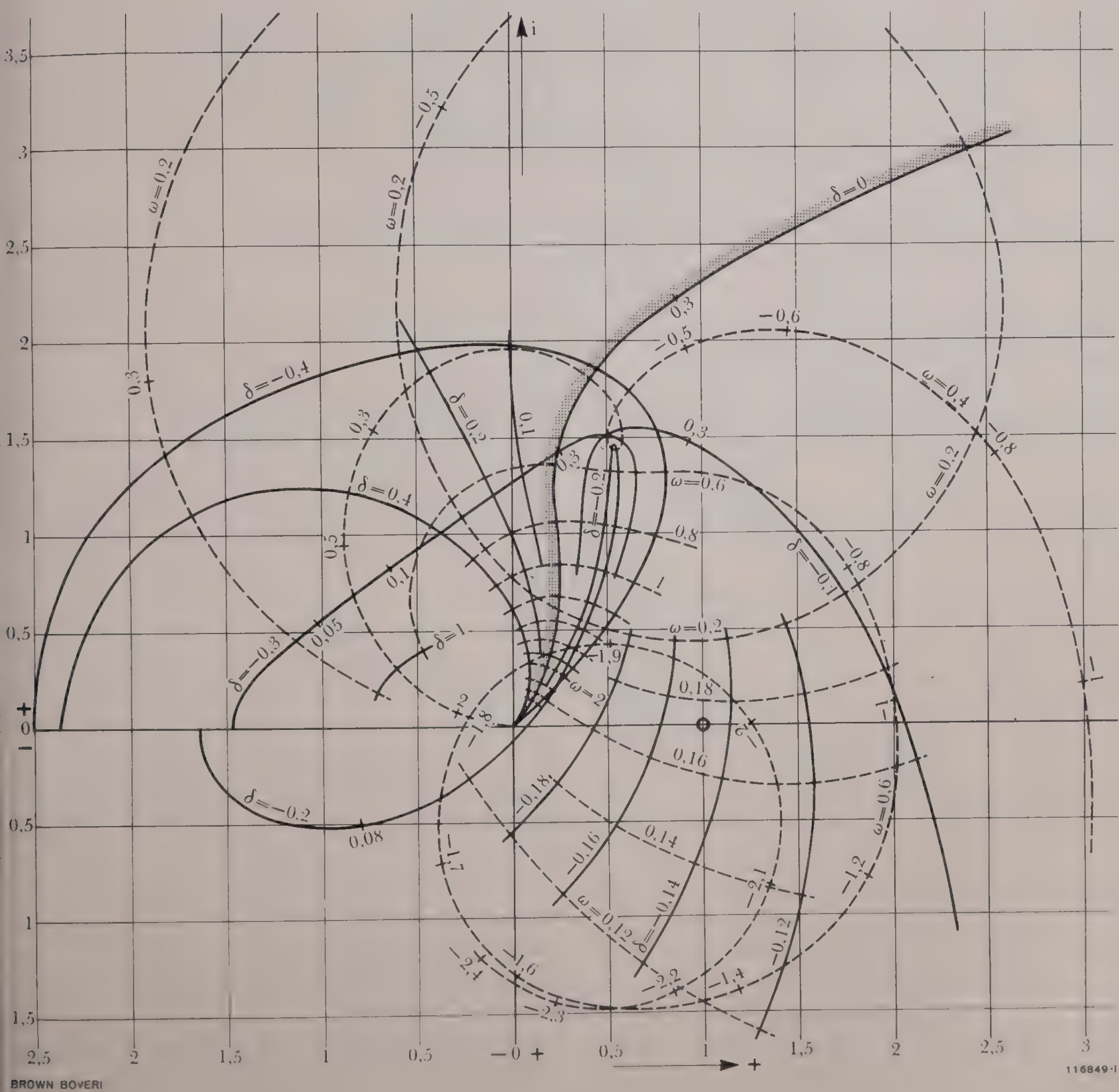
Fig. 8. – Plot of the real axis of the p-plane for the installation with proportional-acting controller ($K_7 = 4$)

Poles: 0 = single
— 0·625 = single
— 2 = quadruple

Fig. 9a. – Conformal map of the p-plane for the installation with integral-acting controller for $T_i = 4$

Mapping for representation of Riemann surfaces and reading off p_2 and p_3.

a



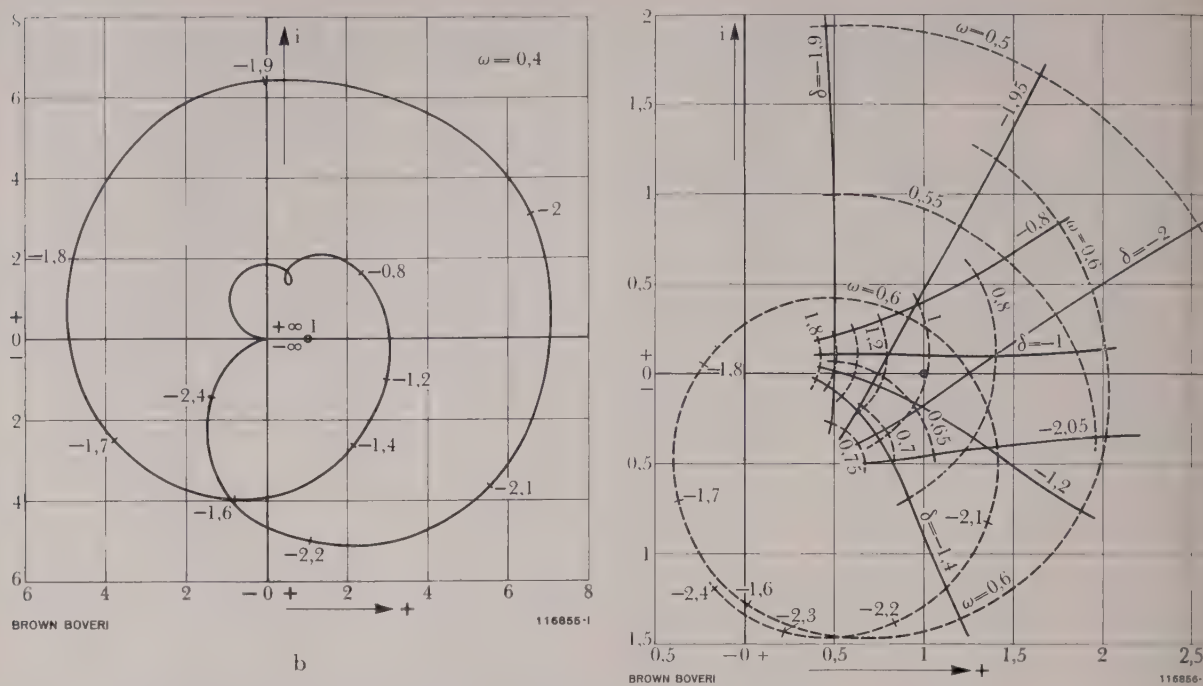


Fig. 9b, c. – Conformal plot of the p-plane for the installation with integral-acting controller for $T_i = 4$

b: The ω-constant parameter line on its path from $+\infty$ to $-\infty$
c: Part of mapping for reading off p_3, p_4, p_5 and p_6

the real axis (Fig. 8) satisfy equation (12). Three complex solutions therefore ensue in the plot of the upper p-plane ($\omega > 0$). They can be read off Fig. 7(a), (b) and (c) as:

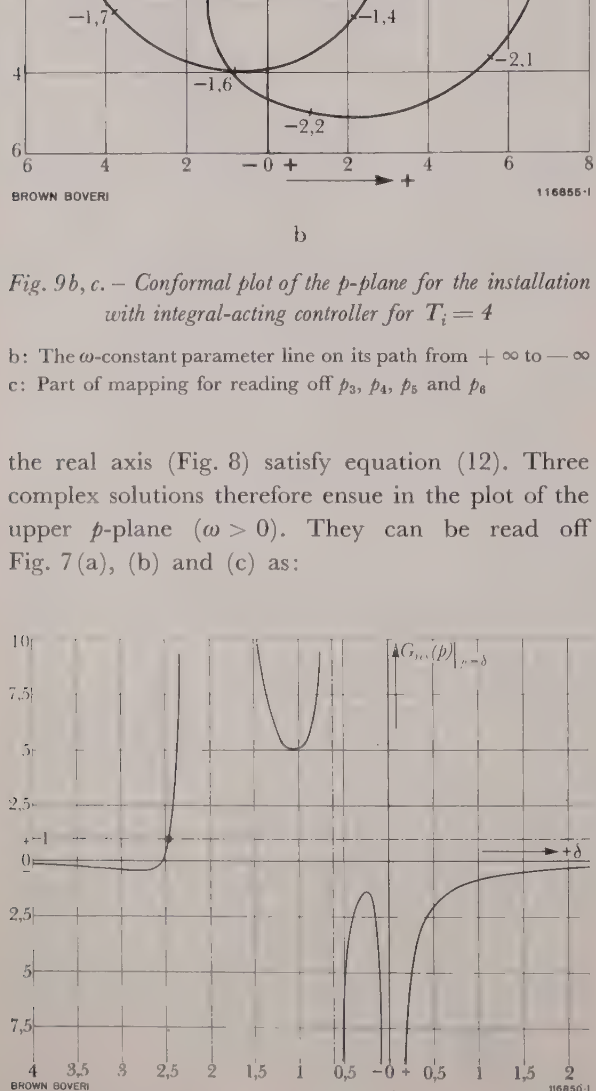


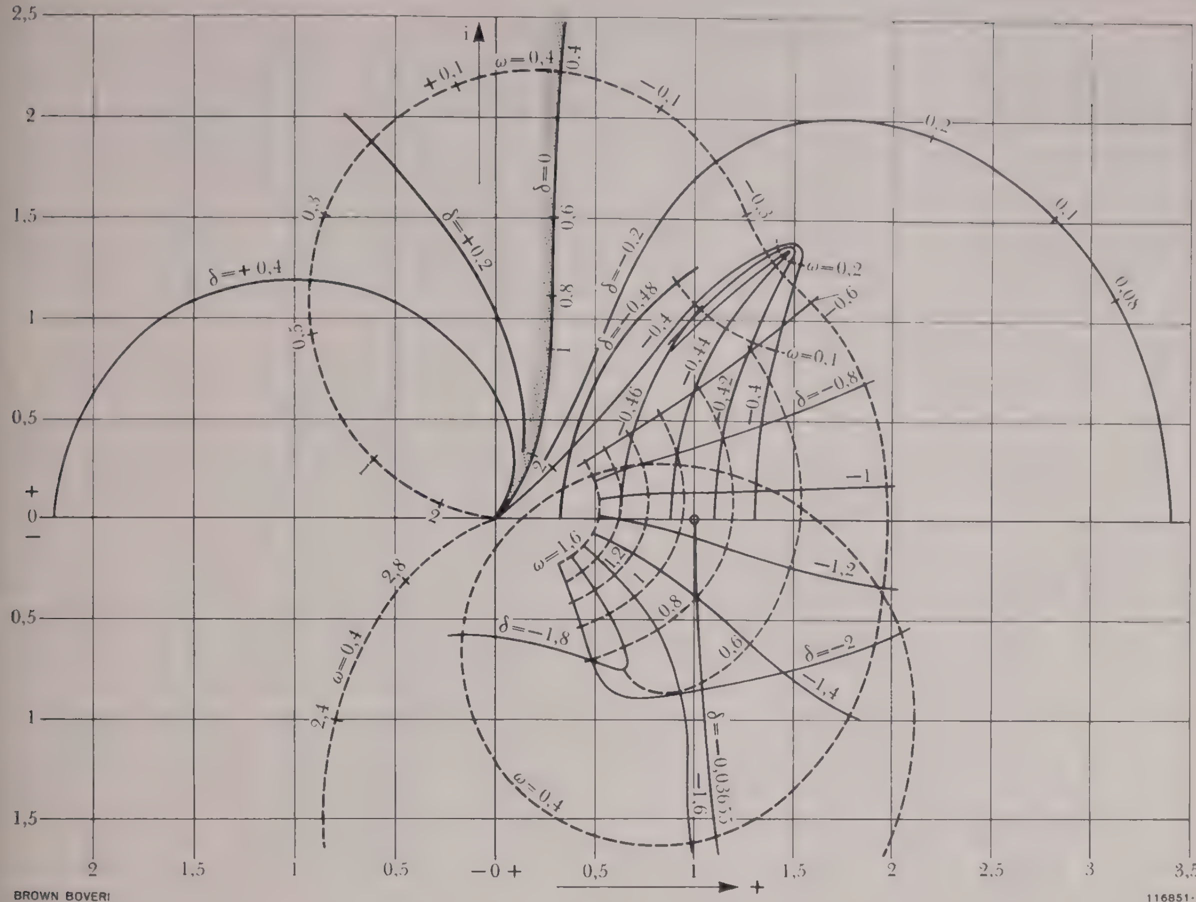
Fig. 10. – Plot of the real axis of the p-plane for the installation with integral-acting controller ($T_i = 4$)

Poles:	0	= double
	− 0·625	= single
	— 2	= quadruple

$$p_{1,\,2} = -0{\cdot}068 \pm 0{\cdot}81\,\mathrm{i}$$
$$p_{3,\,4} = -1{\cdot}44 \pm 1{\cdot}63\,\mathrm{i}$$
$$p_{5,\,6} = -2{\cdot}92 \pm 0{\cdot}785\,\mathrm{i}$$

The relation between the damping factors δ and the oscillation frequencies ω in the individual solutions is arbitrary.

Fig. 9(a), (b) and (c) and 10 give an insight into the system with the integral controller at $T_i = 4$. The mapping of the real axis (Fig. 10) gives a real solution $p_1 = -2{\cdot}45$. Three pairs of conjugate complex solutions remain to be found, since the system is of the 7th order. Fig. 9(a) gives the first pair $p_{2,\,3}$. Although the frequency response for $p = \mathrm{i}\,\omega$ passes at a considerable distance from the point $+1$, there exists, as a fundamental solution, a very lightly damped, slow oscillation, which would never be detected by estimation. In following the lines of constant δ; $\delta = -0{\cdot}1$; $-0{\cdot}2$; $-0{\cdot}3$ and $-0{\cdot}4$, one comes across the interesting fact that these lines, cutting the real axis, wander very rapidly with increasing damping from the positive side through the point $+1$ to the negative side (see in particular $\delta = -0{\cdot}2$) and yield a lightly damped solution. Branch points exist in the small loop of the parameter line $\omega = 0{\cdot}4$ and in the large one $\omega = 0{\cdot}6$. Following the line from $\omega = 0{\cdot}4$ (chosen at random) from $\delta = +\infty$ to $\delta = -\infty$, considering the line extended flat on both sides, it can be seen that point $+1$ is passed through three times (Fig. 9b).

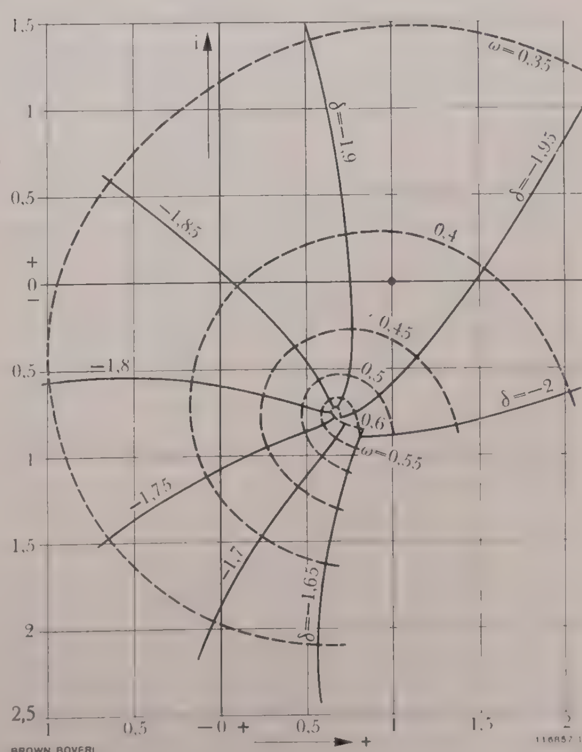


a

Fig. 11. – Conformal mapping of the p-plane for the installation with integral-acting controller for $T_i = 16$

a: Part of mapping for illustration of p_1 and p_2 and reading off p_4 and p_5

b: Part of mapping for reading off p_6 and p_7



b

The line $\omega = -0{\cdot}4$, symmetrical to the real axis does the same. There are thus 6 solutions. The right-hand side of the p-plane ($\delta > 0$) remains to the left of the frequency response curve $G_{res}(p)|_{p=i\omega}$. Fig. 10 gives indication of this: $G_{res}(p)|_{p=\delta}$ is negative for $\delta > 0$. Fig. 9 (c) gives the 4th and 5th solutions, $p_{4,5}$, and the 6th and 7th $p_{6,7}$. The seven solutions are:

$$p_1 = -2{\cdot}45$$
$$p_{2,3} = -0{\cdot}148 \pm 0{\cdot}173\ i$$
$$p_{4,5} = -1{\cdot}07 \pm 1{\cdot}02\ i$$
$$p_{6,7} = -1{\cdot}979 \pm 0{\cdot}622\ i$$

An estimate of the basic solution from $G_{res}(p)|_{p=i\omega}$ in Fig. 9 (a) would perhaps yield p_4.

Fig. 11 (a) and (b) give the solutions for the system with integration time $T_i = 16$.

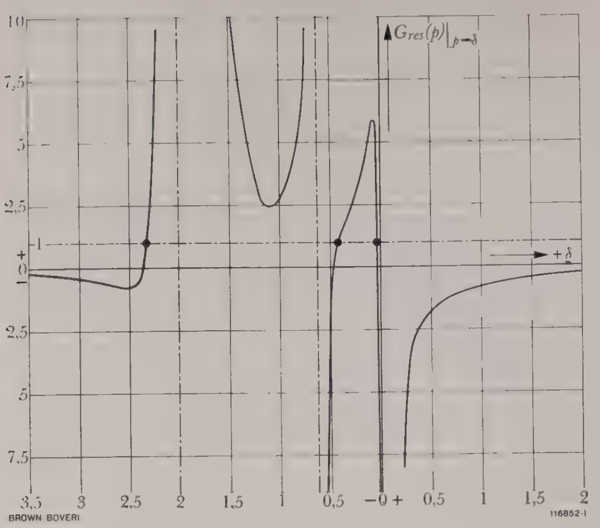


Fig. 12. – Plot of the real axis of the p-plane for the installation with integral-acting controller ($T_i = 16$)

Poles: 0 = double
— 0·625 = single
— 2 = quadruple

$$
\begin{aligned}
p_1 &= -0{\cdot}03655 \\
p_2 &= -0{\cdot}428 \\
p_3 &= -2{\cdot}315 \\
p_{4,5} &= -1{\cdot}11 \pm 0{\cdot}93\,\mathrm{i} \\
p_{6,7} &= -1{\cdot}92 \pm 0{\cdot}418\,\mathrm{i}
\end{aligned}
$$

Here, the mapped real axis, Fig. 12, already yields three solutions. In Fig. 11 (a) the parameter line given by p_1 is drawn in. The family of curves shows how solution p_2 arises. The parameter line $\omega = 0{\cdot}4$ makes two turns and thus indicates two or four solutions, respectively. The first is p_4. A branch exists in the middle of the loop. The sheet developing out of it is Fig. 11 (b): it gives us the last necessary solution p_6 for the frequency spectrum.

Here the estimation of the fundamental behaviour in Fig. 11 (a) would reveal p_4, whereas p_1 would have a decisive detrimental effect in producing a weakly damped aperiodic oscillation, in the case of reference input.

Summary

For the analysis of compound control systems the method of conformal mapping of the total p-plane, in contrast to mapping only the imaginary axis of this plane, known as the frequency response curve, may be chosen for the following reasons:

(a) Even if the frequency response of a control system does not enclose the critical point, it does not guarantee stability of the control.

(b) The generalization of the Nyquist stability criterion becomes necessary, necessitating a knowledge of the number of poles of the transfer function of the broken system $\dfrac{Z(p)}{N(p)}$ in the right-hand p-half-plane.

(c) The determination of the poles for functions of higher order is generally only possible with approximate methods, which may mean considerable expenditure of effort or necessitate having a digital computer at disposal.

(d) Instead of finding the pole and subsequently applying the criterion, the zeros of the closed system $\dfrac{Z(p)}{N(p)} = +1$ can be found directly by the same method. These zeros, the eigen values of the control system, provide a substantially better indication of the behaviour of the system than the frequency response ($p = \mathrm{i}\,\omega$): the latter can indeed, as shown, be misleading concerning the estimation of the damping factor.

(e) The conformal mapping of the transfer function yields, likewise in approximation, all the eigen solutions, but gives in addition a still better insight into the behaviour of the control, especially if control systems are gradually assembled and transfer functions are correspondingly represented. Programmed partial results from the computer then give an insight into the static and dynamic structure of the system.

(f) The root-locus method [7], known as a relatively rapid method for single-loop control analysis, may become very tedious for compound control systems. The reason for this is that in the transfer function, control parameters to be varied may no longer be independent of p. This even holds true for the gain factor of ideal proportional-action controllers.

For these reasons the method of conformal mapping is justified for the analysis of compound systems.

(CI)

R. STARKERMANN

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THE NEW SERIES OF D.C. TRANSFORMERS

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The new series of d.c. transformers were specially developed with regard to the tasks which have to be performed in control systems. They comprise units with current-controlling transductors and ancillary units for feeding, and for forming the output. This organization affords many advantages for their installation and utilization. The directional sensitivity of the units is obtained by measuring the induced voltage in quite a new manner with transistors.

D.C. TRANSFORMERS can be designed according to various functional principles, i.e. as

Transductors with ancillary elements,

Shunts with a vibrator followed by an a.c. amplifier and phase discriminator,

Hall generators with a.c. amplifier and phase discriminator.

By these different methods it is possible to realize transformers with almost equal facility with a transformation error of about 1%. If greater accuracy is stipulated, the outlay for circuit elements increases according to the subsequent demands on the unit. For each of the possible circuit principles, limits are imposed on its application, by the magnitude of the primary current, output power, and insulation level.

The most economical prospects of employment are offered by current-controlling transductors connected in series. They are by far the most suitable for the construction of series of transformers with primary currents above 10 A, for type ratings higher than 1 W, and with insulation between primary and secondary capable of withstanding more than 1 kV.

The d.c. transformers described in this article contain such transductors. To augment them a number of ancillary units are available, which convert the transformer outputs to the standardized signals for the control units of the Brown Boveri electronic system.[1] They are primarily employed in open and closed-loop control systems in power engineering. From this field of application there arose certain stipulations which led to the development of two separate series of d.c. transformers with the following characteristic data:

Primary currents (range of application)	5–400 A	50–7000 A
Insulation of primary (service values)	1 kV	5 kV
Burden suitable for	control, measurement	control, measurement, protection, various
Secondary rating	5 VA	100 VA
Supply	110 V, with power pack: 220 V, 50 c/s	220 V, 50c/s
Secondary current (rated)	0·1 A	1 A
Transformation error	< 1%	< 1%

[1] See page 665.

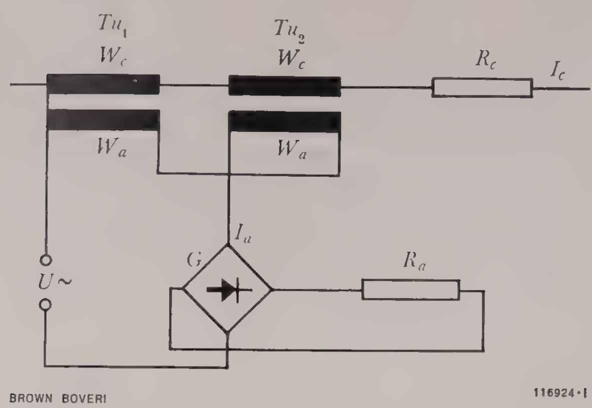

Fig. 1. – Current-controlling transductors in series, with rectified output

$U_{\sim}$ = Alternating supply voltage (r.m.s.)
T_{u1}, T_{u2} = Transductors 1 and 2
W_c = Control winding with N_c turns
W_a = Power winding with N_a turns
R_c = Total ohmic resistance of control circuit
R_a = Transformer burden
G = Rectifier
I_a = Current in power circuit
I_c = Control current

Before going into the design of the transformer series, it is worth discussing the principle of the transductor d.c. transformer briefly. The subject is dealt with thoroughly in various publications, for instance [1, 2, 3].[2]

[2] The figures in brackets refer to the bibliography on p. 775.

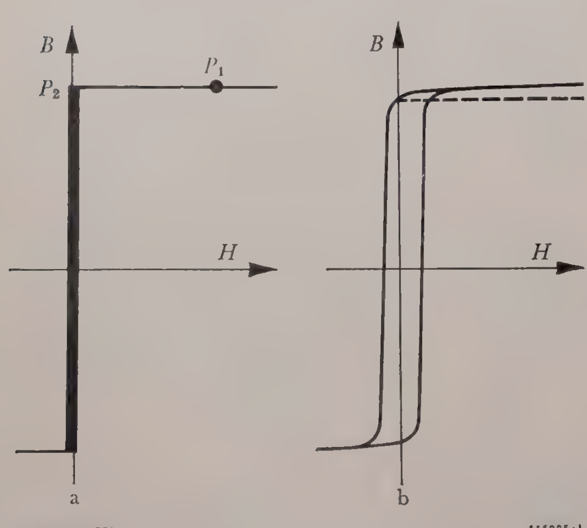

Fig. 2. – Hysteresis loop

a: Ideal
b: Wound-strip core of 50% nickel-steel

Fig. 1 shows the basic circuit of the d.c. transformer with two current-controlling transductors in series. Here current-controlling means that across the whole working range—a transductor is always saturated—there is a fixed relationship between the currents in the control winding and the power winding. Subsequent remarks will assume transductor cores with an ideal rectangular hysteresis loop (Fig. 2a). This results in only slight deviations from actual conditions. If, in the control winding W_c of the transformers one primary current (d.c.) is flowing, both transductors will be magnetized well into the saturation region of their hysteresis loop, e.g. point P_1 (Fig. 2a). The momentary magnetization values are increased by the superposed alternating voltage $U\sim$, in opposition to the control quantity for both transductors. If the control current and a.c. voltage are equal in direction for one core, its magnetization is increased; the inductance of the winding remains zero. At the same moment these two quantities are in opposition in the second core. The a.c. voltage drives a current I_a in the power circuit, having the magnitude

$$I_a = \frac{I_c N_c}{N_a} \tag{1}$$

where

I_c = control current
I_a = current in power winding
N_c = number of turns in the entire control winding
N_a = number of turns in the entire power winding

It is not possible to increase I_a because the core is now just demagnetized as far as the vertical part of the hysteresis loop (P_2 in Fig. 2a). Owing to its infinitely large inductance (assumed for the ideal case), the winding absorbs all the remaining alternating voltage, i.e. $U\sim - I_a R_{a_1}$. Assuming there is a pure direct current in the control circuit, the shape of the current in the power circuit becomes rectangular with no harmonics. The voltage induced in W_a can have hardly any effect on the control circuit because such transformers always have a high transformation ratio, given by N_a/N_c (frequently the number of primary turns is only 1), whereas the control circuits in most practical cases have a relatively high resistance. The changeover in the limitation of the working current between the two trans-

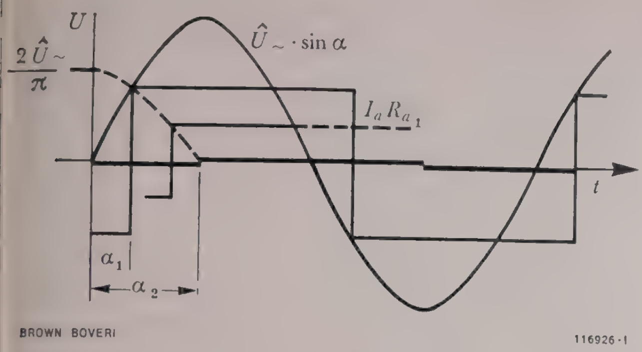

Fig. 3. – Input and burden voltage, as a function of the control angle of the transductor d.c. transformer

α_1 = Limiting angle for rectangular burden voltage
α_2 = Angle for zero burden voltage
I_a = Current in power circuit
R_{a1} = Total ohmic resistance in power circuit
$\hat{U}_\sim$ = Peak value of alternating input voltage

ductors takes place abruptly on account of the sharp changes in the hysteresis loops with an ohmic burden. The working current I_a remains rectangular so long as the voltage required across the burden can be supplied by the alternating voltage. As long as this is true, the condition that one of the cores must always be unsaturated is satisfied. For this limiting point

$$\hat{U}_\sim \sin\alpha = R_{a_1} I_a \qquad (2)$$

and

$$\sin\alpha = \frac{2}{\pi}\cdot\cos\alpha \qquad (3)$$

The limiting angle α_1 works out to 32° 30′.

From this the maximum burden is given by

$$R_{a_1\,max} = \frac{U_\sim}{1{\cdot}11\,.\,I_{a\,max}}\cdot\cos 32^\circ\,30' \qquad (4)$$

where

$R_{a_1\,max}$ = maximum total resistance of power circuit

$I_{a\,max}$ = mean value of the maximum admissible current in the power circuit (in applications, the maximum load current)

$1{\cdot}11$ = wave-form factor

$U_\sim$ = r.m.s. value of alternating voltage = $\frac{\hat{U}_\sim}{\sqrt{2}}$

$\hat{U}_\sim$ = peak value of alternating voltage

Conversion of equations (2) and (3) into

$$\cos\alpha = \frac{R_{a_1}\cdot I_a}{\hat{U}_\sim}\cdot\frac{\pi}{2} \qquad (5)$$

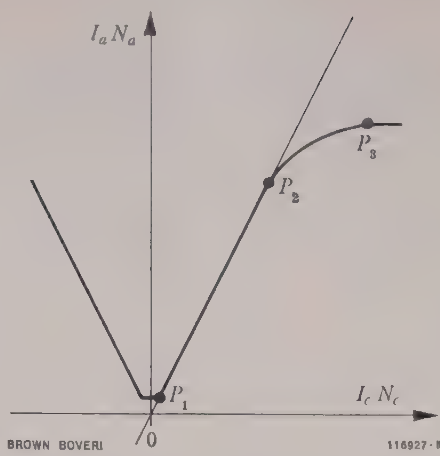

Fig. 4. – Control characteristic $I_a N_a$ = f ($I_c N_c$) of a transductor d.c. transformer

For the ideal hysteresis loop it begins at the origin.

P_1 = Magnetization current × N_a
$P_2 = I_a R_{a1}$ = sin 32° 30′ × $\hat{U}_\sim$
$P_3 = R_{a1} I_c N_c / N_a = \hat{U}_\sim$
N_a = Number of turns in the whole power winding
N_c = Number of turns in the whole control winding

shows that the shift between the working current (changeover point between the two transductors) and the alternating voltage is 90° for the cases R_{a_1} = 0 and I_a = 0 (Fig. 3). If the product $R_{a_1} I_c N_c / N_a$ (equation 1) is larger than permissible for the limiting angle, the control characteristic I_a = f (I_c) ceases to be a straight line (point P_2 in Fig. 4). It changes to a horizontal line when $R_{a_1} I_c N_c / N_a = \hat{U}_\sim$ is attained. The control characteristic is symmetrical about the ordinate.

Deviations from the ideal assumptions result in a deviation from the rectangular form of the working current and affect the accuracy of transformation. In practice such differences occur as follows: The hysteresis loop does not possess the ideal rectangular shape. The changeover from the region of infinite inductance to zero inductance is curved (Fig. 2b). In the region of saturation of the transductors residual and stray fields are experienced. The effects of the latter are stressed in Fig. 4 and 5. The magnetization current of the cores induces a current in the power circuit even when the control current is zero. This affects the shape of the working current at heavier loads, and is noticeable by a slight jump crossing the hysteresis loop at the end of the core

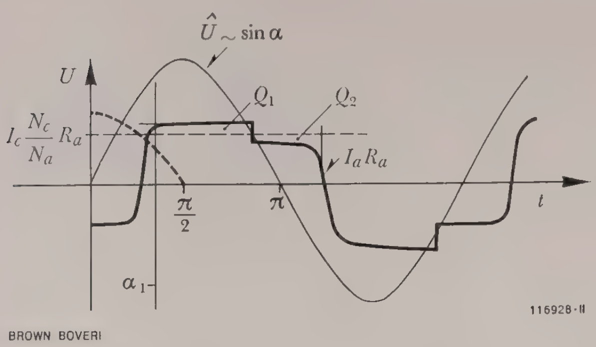

Fig. 5. – Effect of error on the shape of the burden voltage $I_a R_a$

Q_1, Q_2 = Effect of the magnetization current

magnetization, when $I_a R_{a1} = \hat{U}_\sim \sin\alpha$. The error due to the magnetization current is only significant at light loads. It varies across the control range according to the relationship

$$F_1 = \frac{Q_1 - Q_2}{\pi} \qquad \text{(Fig. 5)} \qquad (6)$$

The residual and stray fields delay commutation, resulting in gaps in the rectified working current. The shape of the rising part of the current curve and the magnitude of the error express the course of the magnetization curve of the transductors from the beginning of the bend in the saturation.

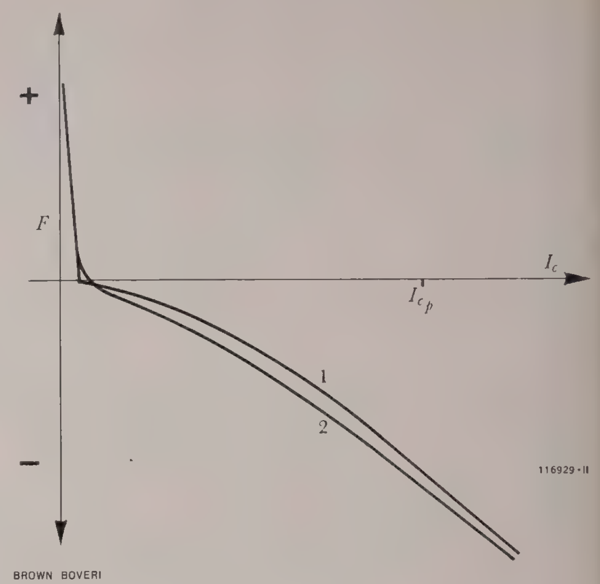

Fig. 6. – Qualitative error curve for the function $F = f(I_c)$ of the transductor d.c. transformer

1 = For the ideal hysteresis loop
2 = Measured on a transformer
I_{cp} = Type rating
F = Error

Fig. 6 shows the qualitative shape of the error curve of a transductor d.c. transformer.

Data of Brown Boveri d.c. transformers

	Type	Primary type current I_{c_T} A	Primary rated current I_{c_n} A	Secondary type current A	Input voltage U + 10% — 15% V	Output voltage V	Maximum admissible burden at prim. curr. $I_c = 4{\cdot}2 \times I_{c_T}$ Ω	Trans-formation error at primary current $I_c = 1{\cdot}4 \times I_{c_T}$ ≤%
Small series	UM34a/7·5	7·5	5–10	0·1	110	45	110	1
	UM34a/15	15	10–20	0·1	110	45	110	1
	UM34a/30	30	20–40	0·1	110	45	110	1
	UM34a/50	50	35–70	0·1	110	45	110	1
	UM34a/75	75	50–100	0·1	110	45	110	1
	UM34a/150	150	100–200	0·1	110	45	110	1
	UM34a/300	300	200–400	0·1	110	45	110	1
Large series	UM33c/75	75	50–100	1	220	100	24	1
	UM33c/150	150	100–200	1	220	100	24	1
	UM33c/300	300	200–400	1	220	100	24	1
	UM33c/600	600	400–800	1	220	100	24	1
	UM33c/1200	1200	800–1700	1	220	100	24	1
	UM33c/2500	2500	1700–3500	1	220	100	24	1
	UM33c/5000	5000	3500–7000	1*	220	100	24	1

* This unit is supplied with an intermediate transformer

Design of the New D.C. Transformers

The d.c. transformer programme is subdivided into a series of high-power units, a series of small units and ancillary units for supplying the voltage to the transformers, and forming outputs with different data.

Fig. 7 shows the internal connections of the units, with the terminal notation. All transformers are equipped with wound-strip cores made of 50% nickel-steel, having a practically rectangular hysteresis loop. Their magnetization current is less than 1% of the rated current. The core material, with its pronounced saturation bend, together with the geometrical dimensions, is responsible for the transformation error being less than 1%.

An interesting feature of the transformers is the range of rated current, which resulted in a minimum number of types. The 100-VA units cover a range from 50 to 7000 A. Partly parallel to the larger series is the series of small units rated from 5 to 400 A. In this range are a number of control systems, for which the stipulations are extremely exacting, but the price of which is unduly high in proportion to the cost of the whole installation. With the small d.c. transformers, a range of inexpensive units is now available, possessing high accuracy, suitable for connection to an indicating instrument and a control unit. The primary current of all the d.c. transformers is 0·7–1·4 times the primary type rating. In this way there is no interruption of the scale of primary currents. In order to exclude damage due to thermal overloading, the transformers are designed to carry a sustained load corresponding to 1·2 times the maximum rated primary current. In the event of load surges they transform the load at maximum burden (see Table) up to three times the rated value. Non-linear resistors can be seen in Fig. 7, to protect the power windings and the load circuit against inadmissibly high voltage peaks occurring under certain circumstances, when the rate of change of primary current is extremely high (short circuit).

The serial notation of the transformers is

UM 33c/... for the large units,
UM 34a/ ...for the small units,

the figures following the solidus representing the rated current.

The transformers are moulded in synthetic resin. Up to a type current of 1200 A the primary conductors are firmly built-in (Fig. 8). In the case of the units type UM 33c 2500 and 5000 the primary bar is not moulded in, because uniform connecting parts for such heavy currents do not bring any advantages as regards the design of the busbars. Hence the transformers can be slipped on over the bars and fastened to them. They can also be mounted on the floor or a wall by feet attached to the outside of the ring.

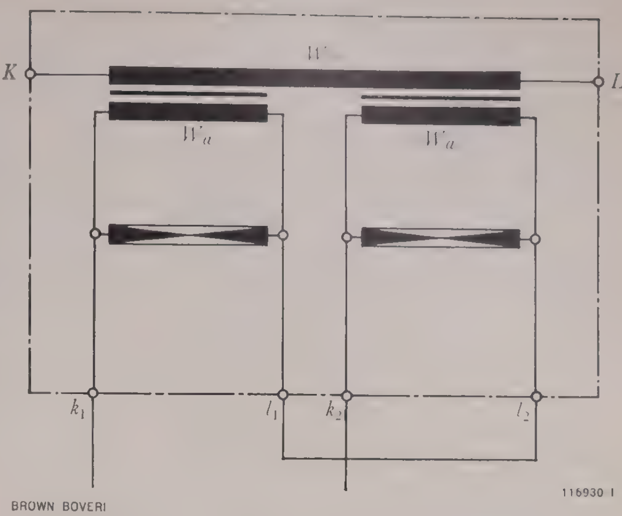

Fig. 7. – Circuit diagram of a d.c. transformer

K, L = Primary terminals
k_1, k_2 = Secondary terminals

Ancillary Units for Use with D. C. Transformers

A constructional distinction must be made between the transformers and the ancillary units, because in many installations—particularly where

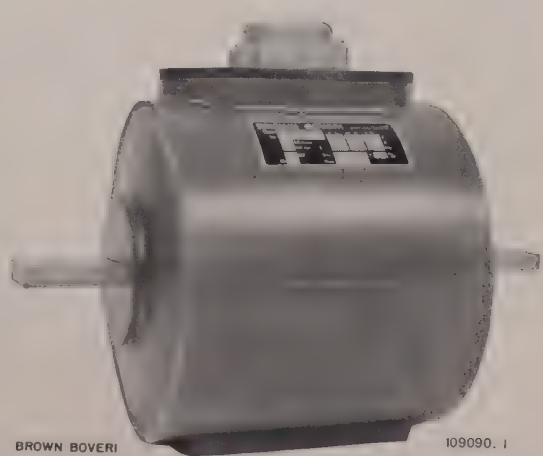

Fig. 8. – Moulded resin d.c. transformer, type rating 600 A

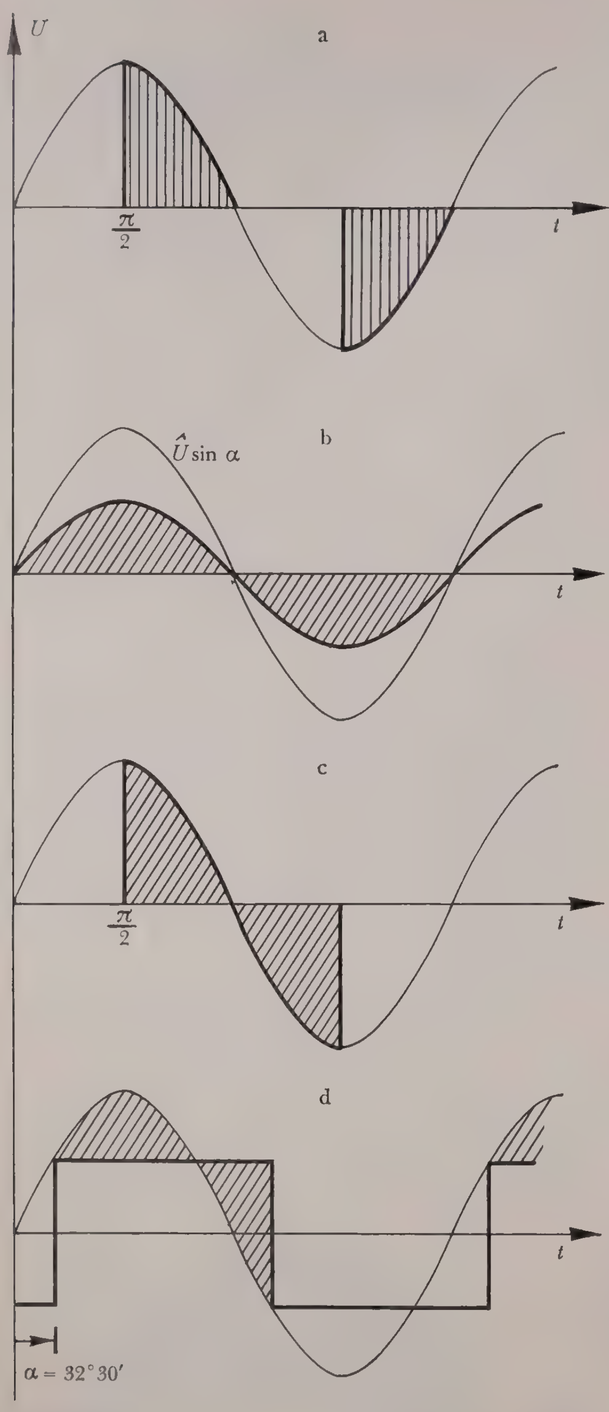

Fig. 9. – Reference voltage in type 5 ancillary unit across one power winding (W_a) of the d.c. transformer between zero and full primary current (shaded areas)

a: Reference voltage for selection of second harmonic according to phase
b: $I_c = 0$
c: $I_c N_c / N_a \approx$ Magnetization current
d: $I_a R_{a1} = \hat{U}_{\sim}$ sin 32° 30′

heavy direct currents are involved—the transformers cannot be accommodated in the switchboard. Since the d.c. transformers are employed for different tasks, a number of types of ancillary units are required. These are designed as independent constructional elements, like the sub-assemblies described on page 673. A transformer of the large series can be loaded with two or three of these sub-assemblies in series. The input resistances of these ancillary units produce the burden of the transformer.

Ancillary unit type 1: Rectified standardized output for small transformers. The unit contains an adjustment resistor, by means of which the output quantity of 15 V d.c. can be set for the primary current range of 0·7–4·2 times the type rating of the transformer.

Type 2: Rectified standardized output for the large series of transformers. This unit possesses the same setting facilities as type 1.

Type 3: Intermediate transformers with an output designed for connection to the Brown Boveri thermal relays type ST. This unit converts the alternating power current of the transformer to 5 A in the range of 0·65–1·45 times the type current.

Type 4: Direct d.c. output. With it the current in the power winding of the large transformers is rectified direct. It is expressly intended for units with a high consumption.

Types 5 and 6: Like types 1 and 2, but intended for measuring primary currents with respect to direction. This kind of measurement is not always possible owing to the V-shaped characteristic of the transductor system. It is, however, achieved by displacing the working point at zero primary current to the middle of one branch of the characteristic, but this enlarges the transformers for the same output, on account of the amount of space occupied for premagnetization. The directional indication realized with the present series of d.c. transformers by evaluating the phase angle of the voltages induced in the transductor windings has, however, no influence on the size of the transformer.

Fig. 9 illustrates the change in the voltage-time area in one power winding of the transformers, in terms of the magnitude and direction of the primary

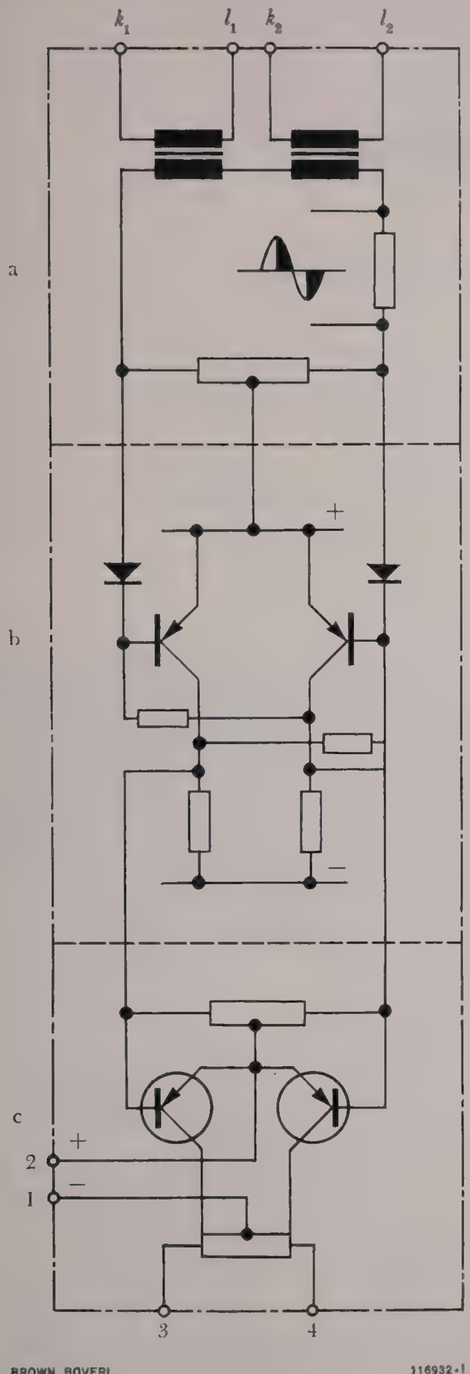

Fig. 10. – Circuit diagram of the type 5 ancillary unit producing a directional transformer output

a = Mixing section
b = Signal amplifier
c = Changeover switch
k_1, l_1, k_2, l_2 = Inputs from transformer
1, 2 = Input of d.c. voltage from transformer burden of ancillary unit 1 or 2
3, 4 = Directional output ± 15 V, ± 5 mA

current. At zero primary current the supply voltage is equally divided between the power windings, which are equal in size. A small control current soon effects a change in the voltage distribution between the two transductors. The second harmonic of the supply voltage then becomes very pronounced. When the control current changes direction, the phase angle of the supply voltage changes relative to each power winding. The peak values of the induced voltages change from $\hat{U}\sim$ for very small burden voltage to $\hat{U}\sim$ $(1 - \sin 32° 30')$ at full load.

In the mixing circuit a of the directional ancillary unit (Fig. 10) the voltages of the power windings, obtained from transformers, are compared with a fixed voltage. The shape of this is like that of the second harmonic. Depending on the direction of the primary current, either a positive or negative voltage from the transformer is added to the reference voltage in the mixing circuit. Voltage peaks higher than the reference voltage are applied via rectifiers to the two inputs of a bistable transistor circuit b, which amplifies the signals and passes them on in rectangular form. A new signal is given after a maximum time-lag of 20 ms following reversal of the primary current. The quantities representing the outputs of ancillary unit 1 or 2 are fed to the directional detector. Their polarity is reversed in a transistor circuit.

Among the various possible versions of the d.c. transformer, the current-controlling series transductor circuit offers most advantages, especially for measuring heavy currents with a high unit output. Brown Boveri manufacture transductor d.c. transformers for control and measurement, with rated primary currents between 5 and 7000 A, their error being less than 1%. This can be reduced to 0·5–0·1% by supplementary means.

(KME) G. HANKE

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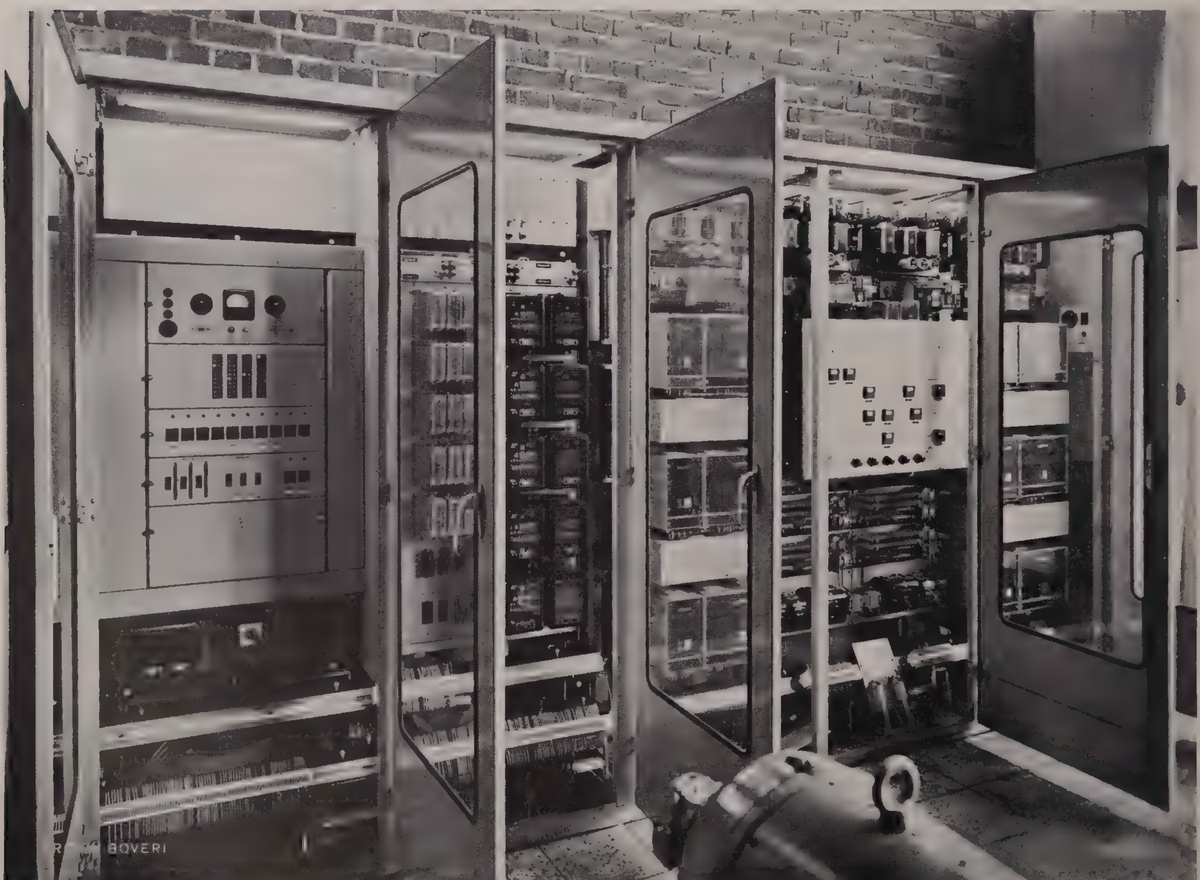
BRIEF BUT INTERESTING

The Digital Decking Device for Mines Winders

622.673.1–83

MINES winders make an ideal subject for automation, on account of their periodically repeated operating programme. If the cage has several decks, but the filling and discharge points only one, it is necessary to move the cage several times in succession so that the tubs can be removed or run on. This process of "decking" is one of the most difficult control tasks there are, because short decking times with exact stopping, free from jerks, are desirable if unloading is to proceed smoothly.

During decking the two cages have to be advanced one deck at a time by commands imparted by push-buttons at the loading point. This task was formerly performed by shaft switches actuated by the cage,



Digital decking device in the control cabinet of a mines winder

In the left-hand section is the decking device, the counters of which can be clearly seen. In the next section is the control gear for automatic operation, in the following sections the magnetic amplifier controllers. This picture shows some of the electrical equipment supplied by Brown Boveri for the No. III winder of the Heinrich Bergbau AG, Essen-Kupferdreh. This is a floor-mounted winder with six-deck cages, with a 1420-kW motor, payload 13·6 t, winding speed 9 m/s.

which gave the commands to brake and stop to the machine through lengths of cable. The decking device now renders these switches and the associated cables superfluous. If abnormal positions are desired for the cage, the device also permits a slow movement in either direction to be performed on receipt of commands from push-buttons.

A decking device was first demonstrated in 1958 at the Mining Exhibition in Essen. Its design, therefore, does not fully conform in all details to the Brown Boveri electronic system. It employs a digital system for measuring distance and for counting. By means of an impulse generator on the braking rim of the driving sheave this measures the distance travelled by the cage, which is counted into an electronic counter as a multiple of a unit distance. Since it is important for correction movement to be possible in both directions, the direction of movement has to be allowed for in counting. Points on the travel, at which the braking and stop commands have to be imparted to the winder, can be set by means of numbered switches and—if necessary, during service—are easily adjustable. The accuracy of setting corresponds to one of the unit distances mentioned (5 mm).

In parallel with this control system is a supervisory system which likewise consists of impulse generators, counters and numbered switches. This stops the cage if it overruns the set stopping point, contrary to the set program. Should this supervisory system fail, the fact is automatically indicated by a built-in self-monitoring system. Visual indication of the momentary counter readings allow the position of the cage to be determined at any time.

Up to now three digital decking devices have been taken into service with pit winders. The first of these has been operating for over a year with a winder for six-deck cages, with a 4800-kW motor, payload 25 t, and a winding speed of 16 m/s. Even before the device was commissioned the advantages over shaft switches were obvious—namely, the reduced outlay for installation and wiring in the shaft, as well as the easy accessibility and interchangeability of all components of the device. In service these were augmented by exclusion of atmospheric effects and mechanical damage, and especially the facilities provided for setting and adjustment. The immediate effect of these advantages was to reduce the time required for erection and commissioning. Experience gained in service proved that stoppages for faults were fewer, resulting in an increase in the tonnage raised. The operating personnel concerned also stress the benefits gained from the removal of the electrical installation in the shaft and concentration of the equipment in the machine room, where the amount of maintenance required is far less.

The combined operation of the different components, such as contactor circuits and transistor circuits, with their considerable differences in current and voltage levels, is perfectly reliable, now that the incidence of noise impulses has been rendered ineffective. Within the year in which this unit has been in service there have been no failures of transistors, cold-cathode tubes and relays, nor any contact difficulties with the plug-in elements.

For setting the command points and on investigating the accuracy of stopping, the visible indication of the counter reading proved to be most helpful. In view of the variation in stopping distances resulting from the braking system, inaccuracy in the control system and varying load, the accuracy of 5 mm for setting has proved quite adequate to permit smooth working at the pit-head.

(KME) R. Gimmel
G. Becker

Drive of a Paper-Machine with a Wire Width of 8300 mm and a Working Speed of 400–900 m/min

676.2.052–83

A few months ago A. Ahlström Oy, Warkaus, Finland, an established customer of the Company, placed an order covering the drive equipment for a newsprint machine with a wire width of 8300 mm and a working speed of 400–900 m/min. As regards capacity, this is probably the largest paper-machine in the world at the present moment, for although machines of comparable width are known to exist in North America, there is no knowledge of their being capable of a top speed of 900 m/min.

This sectional drive with individual generators connected on the unit principle comprises 18 drive units for the various sections of the machine, with an aggregate power of 6100 metric h.p. The twelve generators,

whose total output is 4500 kW, are arranged as three converter sets, each driven by a synchronous motor. The paper speed is adjusted by varying the armature voltage of the generators. To regulate the draw there is a modern system of speed control with a superposed system of angular control of extremely high precision, incorporating units of the new Brown Boveri electronic system, in conjunction with tried elements of established control systems.

Whereas the enormous width presents mainly constructional and technological problems for the machine builders and paper-mill engineers, the increased speed imposes much more exacting demands on the rapidity and accuracy of the control system, both for the working speed and the draw. As the present economical speed for the manufacture of newsprint is around 650 m/min, the programme visualized with this machine has already made allowance for such development in the technological sphere as may be expected in the next few years.

The sectional drive with individual generators designed by Brown Boveri for machines of this size is in many respects superior to the arrangement in which the sections are fed from a busbar system. It affords greater flexibility for manoeuvring and normal operation of individual units, smooth starting with optimum acceleration times, rapid braking to suit the mechanical properties, and simultaneous manoeuvrability of all sections with variable and individually set auxiliary speed. Experience with drives of this kind which have already been completed with the same circuit arrangement, fully confirm the significance of these advantages.

(KME) M. ROHNER

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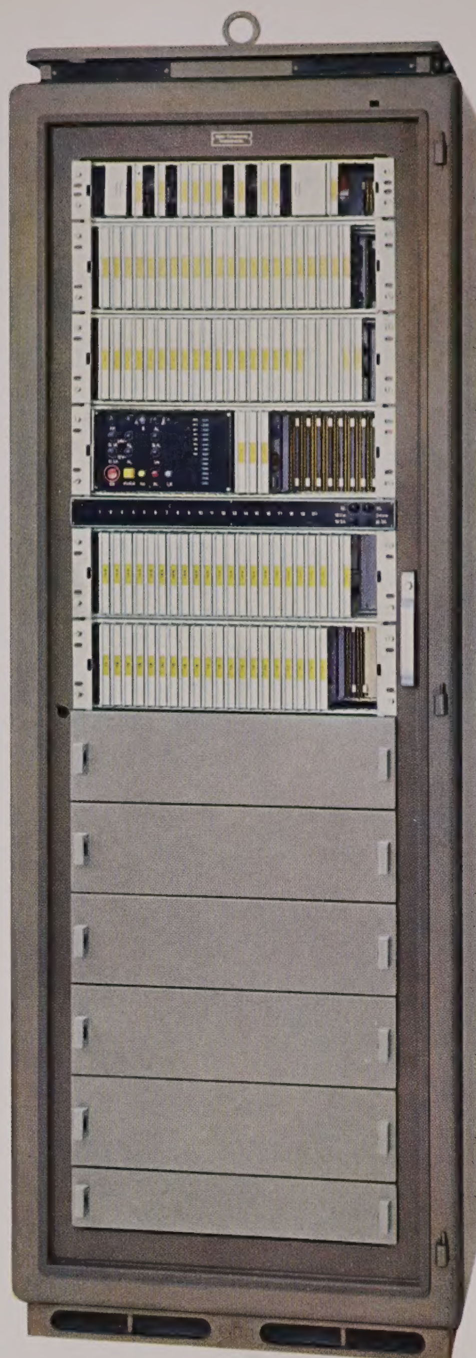

Remote-control cabinet for 20 commands and acknowledgement signals. Opened to show the arrangement of units, sub-assemblies and printed circuits on a hinged frame

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